NUCLEAR PHYSICS IN EUROPE:
HIGHLIGHTS AND OPPORTUNITIES
NuPECC REPORT*

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NUCLEAR PHYSICS IN EUROPE: HIGHLIGHTS AND OPPORTUNITIES

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(an Associated Committee of the European Science Foundation)

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1. Preamble

1.1 The Role of NuPECC

NuPECC is an Associated Committee of the European Science Foundation. Its Terms of Reference state that:

The objective of NuPECC is to:

- strengthen European collaboration in nuclear science through the promotion of nuclear physics and its trans-disciplinary use and application.

In pursuing this objective the Committee shall

- define a network of complementary facilities within Europe and encourage optimisation of their usage
- provide a forum for the discussion of the provision of future facilities and instrumentation and
- provide advice and make recommendations to the ESF and to others bodies on the development, organisation and support of European nuclear research and of particular projects.

Guided by these Terms of Reference, NuPECC has initiated an analysis of ongoing and future research activities in the field of nuclear physics in Europe. The result of this effort is documented in the present report entitled

“Nuclear Physics in Europe: Highlights and Opportunities”.

It follows a previous analysis published by NuPECC in December 1991. It contains a review of the field, recommendations for future developments, and a chapter which describes the present and future possibilities of the corresponding research facilities in Europe. This is the first attempt to define a network of facilities within Europe that include local and national facilities as well as European laboratories which are complementary and guarantee international access.

The report is intended to serve as an input into the decision-making process of the various local, national and international committees and agencies which have to discuss and decide about future investments in the field. NuPECC intends to meet representatives of the funding agencies in order to present this analysis of the scientific perspectives of nuclear physics, and to discuss how the adopted recommendations can be implemented through collaborative ventures in Europe.

The present report only discusses basic research in nuclear physics; the trans-disciplinary use and application of nuclear science have been presented in a report entitled “Impact and Applications of Nuclear Science in Europe: Opportunities and Perspectives” published by NuPECC in December 1994. More detailed information on nuclear physics facilities in Europe (accelerators, major instrumentation, access for foreign users) is contained in the regularly published “NuPECC Handbook: International Access to Nuclear Physics Facilities in Europe”.

1.2 The Preparation of the Report

The decision to initiate a new review of ongoing and future research in nuclear physics was taken by the committee in the beginning of 1996, since the previous exercise had started more than 6 years ago. The work was organised as follows:

The field was defined and split up into six main areas. A letter of charge was sent to the
conveners chosen by NuPECC with the mission to form working groups and to prepare reports which contain highlights and open problems as well as recommendations on how to proceed in the respective sub-field within an international context.

In a first meeting of NuPECC with the conveners it was agreed upon that

- the conveners are free to select the members of their working groups,
- the final reports of the working groups, published as separate chapters in the NuPECC report, are the conveners’ sole responsibility,
- the overall recommendations in the beginning of the NuPECC report reflect only the view of NuPECC.

In March 1996, the working groups were formed and NuPECC members were assigned as liaison persons. From March 1996 through March 1997, intense discussions took place within the community. Town meetings or topical workshops were used as a forum for these discussions. This “bottom-up” approach led to the completion of a first version of the working groups’ reports by April 1997. These reports were displayed on the WorldWideWeb in order to provide the community with an additional opportunity to introduce comments and suggestions.

A workshop was organised in Munich on April 23 to 26, 1997, where the working groups’ reports were discussed for two days between the conveners and NuPECC members. An afternoon was devoted to a discussion with the directors of the major European research facilities (CERN, DESY, GSI, GANIL, Gran Sasso). Following these discussions, a zero-order draft of “NuPECC Recommendations” was prepared. The working groups’ reports and the draft of the “NuPECC Recommendations” were then presented to an audience of about 100 nuclear physicists and intensely discussed.

From April to December 1997, the working groups’ reports were finalised. A NuPECC editorial committee was formed in order to formulate the “NuPECC Recommendations”, the chapter “Towards a Network of Complementary Research Facilities” and the “Introduction”. The final version was discussed and endorsed by NuPECC at its meeting on November 7 and 8, 1997.

1.3 The Structure of the Report

The present report is organised as follows:

- Acknowledgements (blue pages)
- Introduction (blue pages)
- Recommendations (blue pages)
- Towards a Network of Complementary Research Facilities in Europe (blue pages)

The six chapters containing the working groups’ reports (white pages):

- Nuclear Structure under Extreme Conditions
- Nucleus-Nucleus Collisions and the Phase Transitions of Nuclear Matter
- Quark and Hadron Dynamics
- Nuclear and Particle Astrophysics
- Neutrino Physics
- Fundamental Interactions

The first part of this report reflects the views of the committee although these views have been strongly influenced by those expressed by the community. The corresponding pages are printed on blue paper.

The second part contains the reports from the working groups formulated under the responsibility of the conveners. This part is printed on white pages.
2. Introduction

Nuclear physics is the science of atomic nuclei, their properties, their interactions and their constituents. Nuclei are complex quantal systems with a finite number of particles, synthesised by nature from two kinds of nucleon, protons and neutrons. Their binding energies are determined by the interplay between the strong, the electromagnetic and the weak interaction.

At low energies, the nuclear properties are described in terms of nucleons and mesons, with empirically deduced effective interactions between them. Information on these properties is derived from nuclear structure studies using advanced spectroscopic tools.

At high energies, the substructure of nucleons and mesons in terms of quarks and gluons becomes visible. The strong interaction between these fundamental building blocks of matter is described by quantum chromodynamics (QCD). One of the most exciting challenges for modern nuclear physics is to study how the elementary fields of QCD — quarks and gluons — build up particles such as nucleons and mesons, and to investigate the effects of quark and gluon degrees of freedom on nuclear structure and hadron dynamics at short distances.

The structure and the dynamics of hadrons as composites of quarks and gluons are intimately connected. Information on hadron structure is derived from spectroscopy, from improved measurements of form factors and from deep-inelastic lepton scattering. Hadron dynamics enters crucially into the production and propagation of hadrons in complex nuclear systems. A key question in this context, both from the point of view of QCD and for nuclear physics, is about the way in which hadron properties change when they are embedded in nuclear matter. Collisions between relativistic heavy ions allow heating and compressing of nuclear matter and thus create the extreme conditions under which such questions can be explored.

Great efforts are devoted to detecting the deconfinement of the quarks and gluons into a plasma phase within such a hot and compressed volume of nuclear matter.

Nuclear physics has not only many links to particle physics, but also to astrophysics. Modern research in these fields is closely related to the description of the various phases in the evolution of the universe: The experiments to detect the quark-gluon plasma and to study the abundance of the lightest elements, the attempts to model the production of the heavier nuclei and to determine the equation of state of nuclear matter, and the search for neutrino masses and dark matter are motivated by open problems shared by nuclear physics, particle physics and astrophysics.

The five chapters in this report describe the main activities and trends in nuclear physics and their relation to research in these neighbouring fields:

Chapter one discusses the properties of nuclei at low energies and describes the extreme states of such finite quantal systems with respect to their neutron-to-proton ratio, angular momentum and temperature.

Chapter two deals with experiments intended to heat and compress nuclear matter during the collision between relativistic heavy ions and to detect possible phase transitions, in particular the transition to the quark-gluon plasma.

Chapter three discusses the substructure of strongly interacting particles and the dynamics of quarks, in particular the attempts to connect high energy QCD to nuclear physics at low energies.

Chapters four and five set out the various connections between nuclear physics, particle
physics and astrophysics and summarise the recent developments in neutrino physics.

Nuclear Structure under Extreme Conditions of Isospin, Mass, Spin and Temperature

The Physics Case:

Cold nuclei in or near to the valley of stability have been studied by decay spectroscopy, inelastic excitation and nuclear reactions. Their single particle structure and their collective excitation modes are rather well investigated and understood in terms of effective interactions. In particular, the interplay between the independent particle motion and the two-body character of the nucleon-nucleon force is modelled by a mean field, with collective and single particle degrees of freedom.

In spite of this significant progress during the last decades, the extrapolation of our knowledge to hitherto unknown areas of the nuclear parameter space as to higher temperatures or to high angular momenta, to superheavy nuclei or to extreme proton-to-neutron ratios is hampered by the effective nature of our models. It is presently not even possible to predict the limits of the valley of stability. The investigation of nuclei under these extreme conditions is therefore the main object of present-day nuclear structure research.

Fusion reactions are available to study nuclei up to the highest values of angular momentum that nuclear matter can hold. They allow the investigation of the entire range of bound states between the yrast-line, where the nucleus is internally cold and the angular momentum is carried by collective motion, and the line defined by the binding energy of the least bound nucleons of the spinning nucleus.

Nuclear reactions with stable beams allow the production of nuclei away from the valley of stability. Fusion reactions, the fragmentation of relativistic projectiles and fission are used to synthesise nuclei with extreme neutron-to-proton ratios and the heaviest elements beyond uranium. However, a detailed spectroscopy of more exotic nuclei is not yet possible. Only the upgrade of existing fragmentation facilities to increase the production rates and the development of powerful radioactive beam facilities will make these investigations possible.

Highlights and Present Activities:

The new generation of high resolution, highly segmented, full solid angle gamma-ray detector arrays have opened up a window for detailed studies of high spin states of cold and warm nuclei:

- The most conspicuous recent findings have shown the existence of several areas in the nuclear landscape containing superdeformed nuclei. Small systematic shifts in the energy levels of some of the rotational bands of superdeformed nuclei and the observation of such bands with almost identical level spacings in neighbouring nuclei pose exciting problems to nuclear structure theory. The dynamics of the decay between states at large deformation and those closer to sphericity, and the possibility of hyperdeformed shapes are among the intriguing open questions of this research.

Heavy-ion fusion, projectile fragmentation, projectile fission of uranium as well as light-particle induced fission are exploited in order to produce exotic nuclei far from the valley of stability:

- One of the surprising results concerns the discovery of nuclei such as $^{11}$Li exhibiting an extended neutron halo; first detailed studies of these halo nuclei as well as the expectation to find heavier neutron-rich nuclei with a kind of neutron skin have prompted widespread theoretical efforts to understand this new kind of dilute neutron matter.

Our knowledge of the $N=Z$ nuclei with their unusual properties caused by the proton-neutron pairing interaction was pushed to heavier nuclei, and much of the close-by proton drip-line could be mapped out. The doubly magic $^{78}$Ni and $^{100}$Sn nuclei have been observed and their proper study brought
within reach once we have higher intensity beams of unstable nuclei. Experiments and theory are indicating that shell closures may change far from stability, with consequences for the r-process of the nucleosynthesis yet to be explored. Another outstanding achievement is the synthesis of the heaviest elements, up to $Z = 112$, with real prospects of extending the periodic table to even heavier elements.

Experimental progress in this field will strongly depend on the realisation of present and future upgrading and development programmes of radioactive beam facilities. Direct nuclear reaction studies can then be performed with the exotic nuclei as projectiles and in inverse kinematics, allowing single particle orbitals to be identified. Proton radioactivity of nuclei at the proton drip line begins to become a spectroscopic tool, because it makes it possible to identify the shell structure of the initial and final states and the angular momentum transfer. Coulomb excitation using relativistic projectiles will be used to study high-lying excitations of collective nature. Mass measurements with an accuracy of $10^{-8}$ or better will be possible.

New theoretical approaches such as relativistic Hartree-Fock and Monte Carlo shell model calculations have been developed to interpret these new data, in particular high spin states and the properties of nuclei close to the drip lines. Calculations for the shell model single particle structure of the heaviest nuclei have been extended to a high degree of sophistication and will help to guide the experimental efforts to produce the very heavy nuclei at and near those with $Z = 114$.

Collisions at incident energies above the Fermi energy create regions of hot and compressed nuclear matter. Densities of more than three times the normal nuclear matter density have been estimated for relativistic and ultra-relativistic energies. This compression phase is followed by a phase in which the system cools, expands and reaches densities much lower than normal nuclear density.

The present activity in the field aims at the understanding of both the dynamical process leading to the formation of hot nuclei and the nature of the subsequent emission processes. Two phase transitions are predicted and are being investigated: a liquid-to-gas transition and the formation of a quark-gluon plasma.

Evidence for the liquid-to-gas transition is discussed in connection with data on the production of intermediate mass fragments. A caloric curve may be derived resulting from an independent measurement of both temperature and excitation energy of a nuclear system. However, the results appear to depend on the initial conditions of the heavy ion collision, and are not conclusive at this point.

Computer simulations of QCD on a lattice predict that the transition from nucleons and nucleon resonances to a deconfined quark-gluon plasma phase should occur in ultra-relativistic heavy ion collisions. Experiments involving Pb + Pb collisions at 158 GeV/n have been performed in order to produce and identify the quark-gluon plasma and study its properties.

The suppression of $J/\psi$ production in hadronic matter at high energy density is discussed as one of the possible signatures for this phase transition.

**Highlights and Present Activities:**

Substantial progress has been made in the phenomenological description of the dynamical evolution of relativistic heavy ion collisions, and of the hot and dense interaction zone generated in such reactions. This refined understanding is based on exclusive measurements of nucleons, pions, kaons and fragments that became available with a good characterisation of the impact
parameter:

- The measured Bremsstrahlung-spectrum allows the identification of the primary nucleon-nucleon collisions. Various flow modes caused by the collective motion of many nucleons have been observed. These processes are strongly impact parameter dependent and are caused by contributions from nucleon-nucleon scattering, the momentum dependence of the interaction and the mean field.

- The measured hadron yields are consistent with values expected for an equilibrated system. The particle production cross sections measured in heavy ion collisions are explained by a two-step mechanism in a high-density medium of hadrons, consisting in large part of nucleon resonances.

- The unusual suppression of \( J/\psi \) production in Pb+Pb collisions, as compared to the proton + proton, proton + nucleus and sulphur + nucleus systems, may reflect Debye screening at the critical density of a deconfined quark-gluon plasma phase. The di-lepton spectrum obtained in Pb+Pb collisions is taken as an indication that the properties of hadrons are modified in a hadronic environment of high density.

The efforts in this field have resulted in very successful experiments, both in Europe and the US. The detector developments, the data analysis of the high-multiplicity events and a thorough discussion of the signatures for a quark-gluon plasma represent huge progress. However, despite some encouraging signals the phase transition cannot be identified unambiguously. What is needed is the correlated signal from several signatures characteristic of the phase transition. A next generation of experiments is being prepared.

Quark and Hadron Dynamics

The Physics Case:

The properties of nuclei and nuclear reactions at low energies are described in terms of nucleons and mesons, interacting on a scale of 1 fm or larger. The nucleon-nucleon interaction at these distances is described by potentials derived from meson exchange models and adjusted to experimental data. However, nucleons and mesons, by themselves, have a substructure. Quarks and gluons are the building blocks of nuclear matter at small distances, large densities and/or high temperatures, and quantum chromodynamics (QCD) is the theory for the strong force. One of the most exciting challenges of present day nuclear physics is to study the influence of the quark and gluon substructure on the properties and interactions of the hadrons and nuclei, i.e. to connect the QCD and low energy model descriptions. The problem is that this requires an understanding of the region of non-perturbative QCD, and it is not a priori clear how to proceed.

The internal structure of the free nucleons has been studied in great detail. Polarised lepton-polarised nucleon deep inelastic scattering allows to disentangle the contributions of quarks, anti-quarks and gluons to the spin of the nucleon. It is now generally accepted that the understanding of the nucleon spin requires consideration of the gluon contribution, and should take into account the strange \( q\bar{q} \) pairs.

Highlights and Present Activities:

New accelerators or storage rings for electrons and protons, with \( \sigma = 100\% \) duty cycle, polarised beams and polarised targets have recently become available. They have been used to obtain new experimental results:

- Short range correlations between bound nucleons are studied with reactions such as (e,e'p). Recent experiments have provided detailed and accurate information on the occupancy of the mean-field orbitals. The analysis shows that only 70% of the strength is contained in states below the Fermi surface. This result is one of the cleanest signals of nucleon-nucleon short-range correlations. The more direct study of these correlations by the eA \( \rightarrow \) e'pp (A-2) reaction has provided first results.
The understanding of the constituent quark structure in nucleons and nuclei requires high precision measurements of the electric and magnetic elastic form factor as well as of transition form factors to baryon resonances. The observation of parity violation in electron scattering experiments by the interference between weak and electromagnetic interaction, currently planned or being carried out in various laboratories, will provide additional information on the strangeness content of the nucleon.

New approaches will be made to study the spin structure of the nucleon. The various theories put forward differ considerably in their prediction of the amount of spin carried by the gluons. Therefore several experiments have been proposed to measure the amount of gluon polarisation.

Hadron dynamics is being investigated by particle production at threshold using photons or proton-nucleon collisions, and by studies of the modification of the properties of hadrons in a hadronic medium. Such processes can be analysed by an effective theory of hadron interactions based on chiral symmetry.

First results on the production of neutral pions are available. Medium modifications are already expected at normal nuclear matter densities, and should be detectable in pion- or photon-induced reactions on nuclei. They should be enhanced in the higher density and temperature regimes encountered in relativistic heavy ion reactions. Experimental evidence for such a behaviour is found in the di-lepton signals from ultrarelativistic heavy ion collisions.

Nuclear and Particle Astrophysics

The Physics Case:

Major experimental developments in nuclear physics and in astrophysics have caused an explosion of activities in this new field. The goal is to study the evolution of the expanding and cooling universe, to understand the creation of the elementary particles, the nucleons and the lighter elements, the various burning phases of stars, and the production of the heavy elements.

Highlights and Present Activities:

Search for Particles or Radiation Incident from outer Space:

Highlights are the data obtained with the telescopes COBE, HUBBLE, ROSAT and GRO. They cover a large fraction of the electromagnetic spectrum. The X-ray and gamma astronomy are completely new fields which came into existence with the availability of detectors outside the earth’s atmosphere. The origin of the gamma-ray bursts is being explored.

Several large terrestrial detector arrays have been built which are optimised to look for various components of the cosmic radiation incident on the outer atmosphere. First data on the high energy part of the spectrum are just being obtained.

Laboratory Assisted Simulations:

The abundance of stable hydrogen, helium and lithium isotopes, together with the life-time of the neutron and the knowledge that three generations of fundamental particles exist, are the input to an understanding of the “Big Bang Nucleosynthesis”, and thus of the dynamical behaviour of the very early phases of our universe. The production of the heavier elements is dominated by various “cycles”, either hot or cold. The exit from such a cycle depends on the cross section for specific nuclear reactions and on the life-times of the nuclei involved. Radioactive beams allow data to be obtained which are relevant for the hot burning processes in stars. These are cross sections for reactions below or near the barrier, subject to the influence of resonances, the level structure of the nuclei involved, and their respective half-lives.

Recent work has established the importance of the rapid proton-capture process in explosive phases, of the “screening” by the electrons on fusion reaction cross sections far below the barrier, and the role of bound-state beta-decay.
Large computer codes have been devised in order to simulate the various scenarios considered in connection with the evolution of stars, up to the explosive phases, and with the synthesis of the elements. The "physics of neutron stars" depends on the equation of state for nuclear matter, and has been a long-debated topic, stimulated in particular by data on the supernovae 1987A.

Neutrino Physics

The Physics Case:
Within the "Standard Model" neutrinos are assumed to be mass-less, with no electromagnetic interactions, and with only two components for each of the three families, i.e. only left-handed neutrinos and only right-handed anti-neutrinos.

The observation of finite neutrino masses, neutrino-less double-beta decay, neutrino oscillations, electromagnetic interactions of neutrinos or the missing right-handed/left-handed component of the neutrinos/antineutrinos would constitute evidence for physics beyond the "Standard Model".

Limits for these quantities have been derived from studies of nuclear beta-decay spectra, from astrophysical arguments, from neutrino experiments at accelerators and reactors, and from the search for solar neutrinos.

There is no unambiguous empirical evidence in conflict with the simple picture provided by the "Standard Model". However there are also no fundamental symmetries known that would explain this amazing simplicity.

Highlights and Present Activities:
Large efforts are under way to improve the limits for neutrino masses, neutrino oscillations, and for the electromagnetic properties of neutrinos. Such limits result in "exclusion plots" for the oscillation parameters $\delta(m^2)$ and $\sin^2(2\theta)$. Data on neutrino-electron scattering allow limits to be set for the electromagnetic interactions of neutrinos.

Improved laboratory experiments, in which the shape of the beta-decay electrons was measured carefully, have determined the electron-neutrino rest mass to be less than 7 eV.

The solar neutrino experiments GALLEX and SAGE are continuing to take data. One of the highlights is the precision with which GALLEX was calibrated with a reactor-made $^{51}$Cr source. However, it becomes more and more obvious that the "Solar Neutrino Puzzle" is not solved. Therefore the GALLEX experiment has been extended to take data for at least another decade, and a new detector system (BOREXINO) is being constructed.

The double-beta decay Germanium detector experiment is being continued, and the limits for a neutrino-less double-beta decay will continuously be reduced.

Large efforts are being made to develop low temperature detector devices in order to detect dark matter, in particular weakly interacting massive particles (WIMPs).

Trends and Directions
What are the perspectives of nuclear physics? We describe some observations which characterise the research activities presently performed in Europe. They can serve as a guide for future developments.

- A New Challenge: Nuclear Structure under Extreme Conditions. The development of radioactive beams and of a new generation of gamma ray detectors have stimulated various experimental studies of nuclear structure at extreme values of spin and isospin, and efforts to synthesise the spherical super-heavy nuclei around $Z=114$. It appears necessary, however, to encourage and support theoretical work which is necessary to identify the kind of data which might be most sensitive to an understanding of nuclei at their extremes.

- The Co-ordinated Effort to Identify the Quark Gluon Plasma. The search for the quark gluon plasma is being performed
as a huge common effort by various large collaborations in Europe and in the US, guided by an ideally matched interplay of theory and experiment. It has become a demonstration of the way in which nuclear and particle physicists attack the problem of understanding a system of maximum complexity.

- **The Ambitious Goal to Understand the Hadronic Interaction.** Scientists from particle and nuclear physics work together in order to study and understand the hadronic interaction at short distances in terms of non-perturbative QCD. This problem requires a co-ordinated effort from the experimental and the theoretical side.

- **New Possibilities for Research in Particle and Nuclear Astrophysics.** This field is profiting from completely new data obtained by the various instruments operating in space, the possibilities to analyse the dynamical evolution of complex systems in large computer simulations, and the availability of radioactive beams which allow the scenario of such simulations to be defined.

- **The Necessity to Work in Large International Collaborations.** The complexity of modern detection devices, the need to optimise the available time for research at a given facility, and the funding policies of European agencies make it necessary to form large, and in general, international collaborations.

Modern research in nuclear physics has led to impressive technical achievements: Completely new detector concepts for gamma rays and charged particles have been invented, new electronic data handling systems devised, and fast pattern recognition algorithms developed. These achievements will be of use in various other fields of science.
3. Recommendations

General Recommendations

Nuclear Physics focuses on the study of the structure and dynamics of complex systems of particles which build up hadrons and nuclei. Nuclear Physics has also a broad spectrum of applications and a strong impact on other fields of science, as presented in the 1994 NuPECC report on Impact and Applications of Nuclear Science in Europe. Nuclear Science remains fundamental for the development of future energy technologies.

A number of complementary research facilities in the field of Nuclear Physics are established in Europe and are operated mainly by national institutions, funded by national agencies and used by an international community of scientists. The exploitation of this network of facilities is co-ordinated by international advisory boards. This co-ordinated approach has led to a remarkable scientific productivity and coherence in the field. It is therefore very important to maintain the open access to this network.

Future facilities and detectors will considerably exceed today’s systems in size, complexity and cost and will mostly have to be realised in the framework of international collaborations. NuPECC therefore recommends that national funding agencies should become involved already during the planning stage of these new facilities. NuPECC is ready to help in this process. For certain projects such as second generation radioactive ion beam facilities and a future high-energy electron accelerator the necessary steps should be taken soon.

Progress in Nuclear Physics depends not only on a strong experimental programme but also on the excellence of research in Nuclear Theory. NuPECC therefore recommends that universities and research institutes assure the future of this part of the field by appointing young scientists in Nuclear Theory. The European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*) in Trento provides a forum for the discussion of new ideas between theorists and experimentalists. NuPECC recommends that long term financial support for ECT* from European sources be assured.

NuPECC emphasises that universities throughout Europe play a key role for the future of Nuclear Physics, both by providing the basic nuclear physics education and the interface to other disciplines and by being the home base for groups doing experiments at large facilities. NuPECC recommends that the strength of the university home base be maintained.

Nuclear Structure under Extreme Conditions

The understanding of Nuclear Structure has made significant progress in the last decade and, at the same time, has generated a number of challenging new questions. They address the properties of the nucleus at the limits of excitation energy, spin, isospin and mass.

The rapid development of experimental techniques leading to highly efficient detector arrays for gamma-rays, charged- and neutral particles makes the investigation of central issues of Nuclear Structure possible. These include extreme nuclear shapes and their evolution as well as the influence of the thermal environment on collective modes at low and high excitation energy.

The next generation of radioactive ion beam facilities will open the way to the study of new Nuclear Structure phenomena near the drip lines, such as halo nuclei, neutron skins, neutron-proton pairing and exotic collective phenomena. At the same time, they will provide
more insight into the process of nucleosynthesis. Extrapolating from the recent observation of element \( Z=112 \), the synthesis of superheavy elements near the expected island of stability will become within reach with the new generation of high luminosity facilities.

**Nuclear Structure** studies rely on a continuing availability of accelerators providing high quality beams of stable ions and electrons. In order to fully exploit the important recent investments in facilities and instruments, those accelerator laboratories which form a European network of complementary facilities must therefore be supported and further improved.

Nuclear Structure studies at the limits of stability require the highest possible luminosities and detection efficiencies. The European collaborations involved in the development of powerful new detector systems and the operation or the construction of the radioactive beam facilities and the R&D on high power target-ion source combinations should be strongly supported in order to reach this goal.

**NuPECC recommendation**: A study group should be set up in order to investigate the main options for second generation radioactive ion beam facilities in Europe.

**Nucleus-Nucleus Collisions and the Phase Transitions of Nuclear Matter**

Collisions of atomic nuclei at intermediate and high energies address some of the key questions of modern Nuclear Physics. They are the means to study the phases of nuclear and hadronic matter as a function of temperature and density of the system. Several phase transitions are under investigation. At low density and temperature, the nucleus may “multifragment” and evaporate into a cold gas of nucleons and light nuclei. At high density and temperature, hadronic matter may dissolve into the quark-gluon plasma via the associated phase transitions of deconfinement and of chiral symmetry restoration. At energies and densities below this regime, the equation of state of hot and dense hadronic matter may be mapped out.

The quark-gluon plasma phase transition and the equation of state of dense matter are of astrophysical and cosmological relevance, e.g. for the recreation of the conditions as they existed about a microsecond after the Big-Bang, the structure of neutron stars and the evolution of supernovae.

All these experimental activities must be accompanied by theoretical investigations using teraflop computer systems. Recent advances in parallel computer systems offer the opportunity to carry out the necessary tasks.

In order to investigate the phase transitions of Nuclear Matter, the complementarity in energy and the variety of beams of existing facilities should be maintained and existing detectors further developed.

**NuPECC recommendations**: A study group should be set up in order to investigate the possibility of a European effort towards large scale computing.

The realisation of a dedicated heavy ion detector in time for the start of the LHC is endorsed as the highest priority of the high-energy heavy ion community.

**Quark and Hadron Dynamics**

The study of the structure of baryons and mesons in terms of the quark and gluon degrees of freedom offers many new challenges that Nuclear Physics will have to address during the coming decade. Achieving a quantitative treatment of the confinement regime, which cannot be treated perturbatively, is at the basis of a more fundamental description of nuclei in terms of elementary constituents and interactions. At the same time the understanding of quark degrees of freedom is indispensable for the study of Nuclear Matter under extreme conditions such as they occur in the quark-gluon plasma and in astrophysical objects.

Addressing the quark and gluon degrees of freedom requires the development of new theoretical concepts and the investigation of observables through exclusive measurements. The corresponding experiments require high-energy
high duty cycle lepton beams of a luminosity much beyond the ones presently available.

High precision measurements at low energy making the best use of existing facilities using electromagnetic and hadronic probes remain essential.

For the time being, the study of the hadron and quark dynamics at higher energy should be pursued with priority at the existing facilities in Europe and in the US.

NuPECC Recommendation: As a new initiative, a high luminosity and high duty cycle electron facility of at least $\sqrt{s} = 7\text{GeV}$ ($E > 25\text{GeV}$ for fixed target experiments) should be built.

Nuclear and Particle Astrophysics, Neutrino Physics, Fundamental Interactions

The impact of Nuclear Physics on other fields of science is particularly strong for Astrophysics, Neutrino Physics, and the study of Fundamental Interactions.

The knowledge of nuclear properties, in particular of exotic nuclei, and of the nuclear equation of state plays a crucial role in the understanding of many astrophysical objects or events, especially explosive ones. High intensity low energy stable and radioactive ion beam accelerators are essential tools for the measurements of cross-sections relevant for astrophysical processes.

Many of the highly sophisticated techniques used to unravel the neutrino properties are common with Nuclear Physics. The use of the Nucleus to study the fundamental interactions and their symmetries implies a deep knowledge of this complex system and the utilisation of nuclear techniques.

Involvement of Nuclear Physicists in a number of experiments on neutrino mass, double-beta decay and dark matter should be supported, including the development of new techniques using cryogenic and superconducting detectors. High intensity pion, muon and cold neutron beams for the study of fundamental symmetries and rare decays should continue to be available.

NuPECC Recommendation: An underground accelerator for background free measurements of important astrophysical cross-sections at thermal energies should be constructed.
3. Recommendations
4. Towards a Network of Complementary Research Facilities in Europe

The scientific achievements and visions of nuclear physics outlined in the present report are intimately connected with the availability and development of the corresponding research facilities in Europe. The exciting broad research programme foreseen for the coming years requires a variety of complementary small and large-scale facilities, with accelerators covering a wide range of particle species and energies, high intensity neutron sources and versatile underground laboratories. It is one of the main goals of NuPECC to help in creating a network of research facilities for nuclear physics in Europe that includes local initiatives, national facilities, as well as European laboratories, which are complementary and guarantee international access. In the present report NuPECC identifies as future directions of research the following areas: nuclear structure under extreme conditions; nucleus-nucleus collisions and the phase transitions of nuclear matter; quark and hadron dynamics; nuclear and particle astrophysics; neutrino physics and fundamental interactions. The status of the requisite facilities that are available will be reviewed in this chapter, with the focus on both present and future aspects of their programmes.

Facilities for the Study of Nuclear Structure under Extreme Conditions

For the study of nuclei at high angular momenta and extreme shapes as well as for the investigations of their thermal response, high efficiency, high resolution multi-\(\gamma\) detector arrays, in combination with heavy ion accelerators with energies around the Coulomb barrier are needed. Such facilities are the Tandem-Linac combination (ALPI) in Legnaro (Italy), the present site of EUROBALL, which is a world-wide unique \(4\pi-\gamma\) detector array constructed by six European countries, the Tandem Accelerator Vivitron in Strasbourg (France), and the cyclotron in Jyväskylä (Finland). These facilities are complementary in the type of heavy ion beams supplied and in the availability of additional special equipment needed to perform modern nuclear structure studies. For the study of fundamental nuclear excitations with high energy resolution, the superconducting cyclotron AGOR at Groningen (The Netherlands) provides unique high energy light ion beams including 200 MeV polarised proton and deuteron beams. The nuclear structure programmes with stable ion beams rely on the continuing availability of accelerators providing high quality beams throughout the periodic system; these facilities, which already form a complementary subnetwork, will need to be further supported and improved (see Figure 4.1).

Intensive studies of the structure of nuclei far from stability are in progress at several European laboratories. These are GANIL in Caen (France), GSI in Darmstadt (Germany), ISOLDE at CERN (Switzerland) and the facilities in Jyväskylä (Finland) and Louvain-la-Neuve (Belgium). By making use of modern ISOL-type sources, recoil or projectile separators in combination with highly sophisticated detector devices, different approaches can be exploited to reveal the properties of nuclei with extreme isospin. The UNILAC of GSI is devoted to a very successful synthesis programme of the heaviest elements. First generation radioactive beam facilities are in operation at GANIL, GSI, and Louvain-la-Neuve and under further development in these and other laboratories. They are complementary in the production process used, the isotopes available, the energy range and in particular in the instrumentation needed.

In Louvain-la-Neuve, the first radioactive
which complement the large facilities. Taken together, they form a comprehensive and well-balanced European network for creative nuclear research. This network rests and relies on a number of regional nuclear physics laboratories spread throughout Europe, which are of great importance not only because they fulfil an educational need by attracting students from universities but also because they are the roots of the programmes carried out within the network.

The European network of nuclear physics facilities is both competitive and complementary to current and projected installations outside of Europe. At the same time we should be alert to opportunities in Europe for innovative development and new facilities in the future. As discussed and substantiated in the present report, several actions should be taken now to ensure that the new challenging problems of nuclear physics can be addressed properly and successfully.
NUCLEAR STRUCTURE UNDER EXTREME CONDITIONS

RADIOACTIVE ION BEAMS

GANIL
30 - 80 MeV/u

LOUVAIN - la - NEUVE NUCLEAR ASTROPHYSICS

GANIL - SPIRAL
2 - 25 MeV/u

CATANIA - EXCYT
5 - 10 MeV/u

REX - ISOLDE
CERN
0 - 2 MeV/u

GSI
100 - 1000 MeV/u
SIS - FRS

HIGH SPIN / HIGH EXCITATION

AGOR - KVI
p, d

JYFL
JYVÄSKYLÄ

VIVITRON
STRASBOURG

ALPI
LEGNARO

RIKEN (JAPAN)

MSU upgrade (USA)

Figure 4.1:
NUCLEUS - NUCLEUS COLLISIONS: THE PHASE TRANSITIONS OF NUCLEAR MATTER

Figure 4.2:
QUARK AND HADRON DYNAMICS

Figure 4.3:
5. Nuclear Structure under Extreme Conditions of Isospin, Mass, Spin and Temperature

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5.1 Introduction

The atomic nucleus is a finite quantal system made up of strongly interacting fermions. Its properties are shaped by the interplay of electromagnetic, weak and strong forces. The study of the nucleus presents many aspects which challenge our understanding, ranging from many-body manifestations of nuclear properties to the forces between nucleons in the nuclear medium and their relationship to the underlying fundamental interactions. Knowledge obtained in modelling the nucleus is useful for the description of other extended quantal systems such as metallic clusters, quantum dots, high-$T_c$ superconductors and Bose-Einstein condensates. The three-body models developed for the description of weakly bound nuclei can be applied to similar problems in atoms, molecules and hypernuclei.

In spite of significant progress during the last decade, we are still lacking a precise and complete knowledge of the behaviour of the nucleus. For example, it is currently impossible to predict even the exact limits of stability. In the course of recent studies, new questions have emerged about the properties of the nucleus at the limits of excitation energy, angular momentum, isospin and mass. Penetration to unexplored extremes in these quantities is likely to reveal fundamentally new phenomena. The first observations along this way are, the new state of matter associated with the halo nuclei, the surprising breakdown of the established magic numbers and the existence of extremely deformed shapes in nuclei.

One major reason for the study of exotic nuclei, i.e. nuclei with extreme values of the proton-to-neutron ratio $Z/N$, is to provide more basic data, for increasingly unstable systems, that will help to answer these open questions. One excellent example is our new understanding of shell structure based on how shell closures develop as proton and neutron numbers change. Another outstanding achievement, which generated head-lines in the press, is the synthesis of the new elements $Z=109–112$. There is now a real prospect of expanding the Periodic Table to even heavier elements. Investigations at the limits of existence, at and even beyond the drip-lines, have revealed new and completely unforeseen structures. Pushing the $N/Z$ ratio to extreme values has resulted in the discovery of halo nuclei and new exotic nuclei at or near the proton and neutron drip lines. They present interesting problems in themselves and lead to a deeper comprehension of the nucleus in general. The detailed study of halo nuclei and the mapping of much of the proton drip line, are among the first fruits of these developments. The doubly magic $^{78}$Ni and $^{100}$Sn nuclei have been observed and their detailed study brought within reach once we have higher intensity beams of unstable nuclei. Data on nuclei far from stability are prime ingredients in astrophysical network calculations, especially for high temperature explosive phenomena. Many unstable nuclei drive astrophysical stellar scenarios. Such
nuclei, which do not exist on Earth, are now becoming accessible at radioactive nuclear beam facilities.

At the extremities of excitation energy and angular momentum nuclear structure studies are probing nuclear shapes and their evolution, the influence of the thermal environment on low modes of excitation and giant modes of excitation. The most conspicuous findings have concerned superdeformed bands and the spectroscopy of strongly deformed shapes. Small systematic shifts in the energy levels in some of these bands have revealed new symmetries in the rapidly rotating quantal system. Equally surprising was the observation of superdeformed rotational bands with almost identical level spacings in neighbouring nuclei. The dynamics of the decay between states at large deformation and those closer to sphericity, and the possibility of hyperdeformed shapes are among the most intriguing questions in this research.

Current theoretical models are stretched to their limits to encompass the wealth of observed new phenomena. One of the strengths of present nuclear theories is the ability to describe simultaneously single particle and collective modes of excitation, whose coexistence at the same excitation energy is one of the most striking and original features of nuclear dynamics. In the new regions of the nuclear chart, mean field theories, large scale shell model descriptions and cluster models are the necessary tools to achieve this goal. Our ability to cope with this new physics relies heavily on improving our knowledge of the effective interaction of the nucleons in the nuclear medium even at low densities. Already, significant progress has been made in developing mean field theories and theoretical approaches which use effective interactions or effective Lagrangians to describe low-energy nuclear states. The rapid growth in computational power has allowed us to calculate the complicated wavefunctions which are needed for a full shell model description of the ground state and low-lying collective states of medium mass nuclei. In even heavier nuclei, ingenious stochastic methods allow the sampling of the very large configuration spaces needed to describe the strength distribution of many kinds of collective modes.

Physics research with exotic as well as stable nuclear beams is in an exciting period of evolution. Most of the striking new results have been obtained by scientists using the very attractive facilities presently available in Europe. Innovative developments in ISOL and fragmentation techniques have played an important role in allowing us firstly to observe, and secondly to study, nuclei much further from stability than ever before. Of vital importance has been the continuing innovation in instrumentation, with advances in highly efficient ion sources and accelerators, recoil-separators, traps and storage rings, ultra-sensitive detection of nuclear radiation with high resolving power, fast data acquisition and modern hardware and software for computing. These developments have opened up new frontiers. In studies of high spin excitations, powerful detector arrays, based on Compton suppressed Ge detectors have been in full operation. Coupled with recoil in-flight separators their selectivity and sensitivity will be further enhanced, allowing studies of excited structures of nuclei very far from stability. The more advanced spectrometer EUROBALL, constructed by a broad European collaboration, is poised to produce its first results at the time of writing. In future, the development of gamma-tracking detectors will lead to the construction of gamma-ray spectrometers with even better performance.

Over the next decade we expect dramatic improvements in our knowledge and understanding of how nuclei respond as we vary their temperature, subject them to rotational stress, and alter both their mass and their isospin. In this report we wish to outline the main directions and goals of this research effort within the European context.

5.2 Nuclei far from Stability

The study of exotic nuclei, far from the valley of beta stability, presents an important challenge for nuclear physics. Nuclear models have to be radically improved in order to accommodate the wealth of new phenomena that have been unveiled by the continuing experimental work.
Prominent milestones are: the discovery of the heaviest chemical elements; the discovery of nuclear halos in the lightest neutron-rich nuclei, immediately followed by a widespread theoretical effort that has considerably advanced our understanding of this phenomena; the experimental mapping of the nuclear shell structure far from stability, reaching in some cases the neutron or proton drip lines.

Although we are still far from having a unified theoretical description valid far from stability, important progress has been made. New clues to the isospin dependence of the spin-orbit field have been given by the relativistic mean field calculations, and the study of the role of the proton-neutron pairing is being actively pursued in $N=Z$ proton rich nuclei and this may provide new insight into the properties of the mean field of nuclei far from stability. The most detailed description of nuclear structure is given by the shell model and new techniques such as the Shell Model Monte Carlo Method may greatly help in dealing with the heavier nuclei. In this context, there have been improvements in the use of interactions obtained from nucleon-nucleon potentials that fit the N-N phase shifts.

There are some aspects specific to the theoretical description of drip line nuclei, for example how to deal with resonant quasi-bound states. This calls for new developments regarding the treatment of the continuum and the correlations — particularly pairing — on the same footing, including few-body dynamics. Another example is the possibility of enhanced charge symmetry breaking due to Coulomb effects in quasi-bound orbits. The low-energy behaviour of giant resonances in drip line nuclei has also raised a lot of interest recently, be it soft dipole “pigmny” resonances or threshold peaks of the dipole and quadrupole channels.

Many new features of nuclear structure have been found — or are predicted to show up — in the realm of exotic nuclei, a few of which are singled out in the following.

- **Halos:** Outstanding structural drip-line phenomena with extreme clusterisation into an ordinary core nucleus and a veil of halo nucleons - forming exceptionally dilute neutron matter. The origin is only partly understood, but a prerequisite is low angular momentum for the halo particles and few-body dynamics such as in Borromean nuclei characterised by pairwise constituents with no bound states. In the limit of vanishing binding extremely large halos may occur.

- **Skins:** For a large neutron excess, the bulk of the neutron density is predicted to extend beyond the proton density creating a sort of “neutron skin”. Similar effects may appear for a large proton excess. There are many suggestions how these skins might change nuclear properties. One could imagine different deformations of the neutron and proton distributions etc.; first experimental observations and theoretical work hint into this direction. It provides the opportunity to study the behaviour of abnormal nuclear matter with very large $T_2$. This could be helpful for improving the reliability of calculations of the properties of neutron stars.

- **Shell stabilisation:** It has been verified that the heaviest elements owe their existence to the $N=162$ neutron deformed shell closure. These results strongly indicate that even heavier elements are shell stabilised.

- **Vanishing of shell closures:** Theory and experiment are now indicating that shell closures may change far from stability. A well-known example is the disappearance of $N=20$ as a neutron magic number in the neon, magnesium and sodium isotopes. But the physical mechanism which is responsible for this disappearance could have other consequences for nuclei of increasing instability such as refection of the shell gaps thus allowing many-particle, many-hole excitations to become more favoured in energy, leading to shape changes and shape coexistence.

- **Nuclei with $N=Z$:** When protons and neutrons occupy the same orbitals, mutual reinforcement of the shell gaps may lead to a stabilisation of exotic shapes in the ground state. Here also the proton-neutron pairing interaction is exposed to view at its maxi-
mum. The study of isospin symmetry breaking, particularly for the heaviest mirror nuclei, is also of strong interest. As for medium heavy nuclei, the \( N = Z \) line coincides with the proton drip-line, proton decay from discrete excited states is possible, as recently observed in \( {}^{58}\text{Cu} \).

- **Superdeformation and hyperdeformation:** Far from the line of \( \beta \)-stability, medium heavy nuclei may exhibit large deformations, even at low excitation energies. Thus it has been shown that \( {}^{76}\text{Sr} \), \( {}^{80}\text{Zr} \) and \( {}^{100}\text{Zr} \) are amongst the most deformed nuclei known in their ground states. Recently a sequence of superdeformed states has been observed in \( {}^{80}\text{Sr} \) and it is predicted that hyperdeformed states should exist in nuclei in this region as well.

### 5.2.1 Exploring the nuclear landscape

Today, our knowledge about nuclei, is restricted to about 2500 of the potentially existing 6000 combinations of protons and neutrons (see Figure 5.1).

![Figure 5.1: The nuclear landscape. Black squares indicate the stable nuclei, the coloured nuclei are the 2500 nuclei synthesised so far. For many of them only their existence is verified today and basic nuclear properties need to be measured. The drip-lines are from the macroscopic-microscopic FRDM model by Möller & Nix.](image)

Depending on the balance between the nuclear force and the Coulomb force, the limitations imposed on this number are the following: the western shore of the chart of nuclei, the proton drip-line, is reached when the binding energy of the last proton becomes zero. Correspondingly, the eastern shore is approached when the binding for the last neutrons vanishes. For the heaviest elements, the disappearance of the fission barrier defines the northern edge. Shell closures are the characteristic landmarks in this continent. In the following, we sketch the recent highlights in the mapping of this landscape including the shores and note that future advances will depend upon a significant increase in the available luminosity.

**Nuclei at the drip-lines and around closed shells.**

Milestones were reached with the fragment separators at GANIL and GSI. The availability of intense primary beams, made from isotopically enriched material such as \( {}^{36}\text{S} \), \( {}^{48}\text{Ca} \), \( {}^{112}\text{Sn} \) was an essential component of these experiments. In the \( N=20 \) region, one surprise was the instability of the semi- and doubly- magic \( {}^{26}\text{O} \) and \( {}^{28}\text{O} \). Decay measurements in the region around \( {}^{44}\text{S} \) gave the first evidence for an unexpected deformation around \( N=28 \), shedding light on the astrophysical isotopic-abundance anomaly in this region. Coulomb excitation experiments with radioactive beams have started to map the deformation in the \( N=20–28 \) region.

Fission has been the richest source of neutron-rich intermediate-mass nuclei. Historically, the bulk of these nuclei (\( \approx 500 \)) were made at reactors. Now fission from fast particles has become an important tool with great future potential. It is employed for fissioning targets at ISOL-type separators and for fissioning projectiles at fragment separators. The discovery of the doubly closed-shell nucleus \( {}^{78}\text{Ni} \), \( Z=28, N=50 \), in the fission of 750 MeV/u \( {}^{238}\text{U} \) projectiles is an important landmark. Nuclear properties in this region are relevant to the understanding of the astrophysical r-process path. More than 100 new neutron-rich nuclides were identified from \( {}^{62}\text{V} \) to \( {}^{166}\text{Nd} \), covering nearly 40 atomic and 100 mass units. Highlights from the ISOL technique are the first synthesis of Ag and Cd isotopes located on the r-process path and the study of single particle states around \( {}^{132}\text{Sn} \), \( Z=50 \) and \( N=82 \). Very neutron-rich neutron emitters of refractory elements are now acces-
sible by the IGISOL (=Ion Guide ISOL) technique.

The fragment separators have also been very successful on the western shore of the nuclear chart. Precision spectroscopy of $^{37}$Ca and $^{40}$Ti has now become possible and will be of prime importance for the calibration of the Cl- and Ar-based solar neutrino detectors. Studies of nuclei near or at the proton drip-line ranging from $^{22}$Si to $^{100}$Sn have become possible. The new nuclei $^{45}$Fe and $^{49}$Ni are the most proton-rich nuclei ever produced. The long awaited synthesis of the heaviest self-conjugate $Z=N=50$ $^{100}$Sn paves the way for future experiments. Studies of rp-process relevant nuclei close to the proton drip-line are successfully started.

Fusion-evaporation reactions will continue to be an important tool in studies of proton-rich isotopes. This is e.g. shown by the $^{100}$Sn mass measurement and ISOL experiments where the heaviest known $N=Z$, odd-odd nucleus $^{94}$Ag was identified.

For $Z=82$, a large number of new isotopes close to the proton drip-line were detected with recoil separator techniques which also allow the investigation of the fission properties of hitherto inaccessible species. Close to $N=126$ ISOL techniques allowed the study of $^{215}$Pb and $^{217}$Bi.

To probe the contributions of closed shells in a fissioning nucleus, e.g. the $N=162$ neutron shell, and in nascent fragments, e.g. at $Z=50$ and $N=82$, even more neutron-rich isotopes beyond those presently known are needed for the heavy actinides and transactinides. Fusion-evaporation and multinucleon-transfer reactions with radioactive beams will provide the only access to this neutron-rich region.

European laboratories active in the use of the ISOL technique are CERN, GANIL, GSI, Jyväskylä, Louvain-la-Neuve, and Studsvik.

**The heaviest nuclei, synthesis and chemical properties**

The discovery of elements 110, 111, and 112 with SHIP at GSI was certainly the outstanding highlights at the top end of the Periodic Table. The results of these fusion experiments, have clearly demonstrated the existence of shell-stabilised nuclei. Very good agreement between these experimental results and theoretical calculations indicate that this region of, presumably deformed, superheavy elements will extend into the island of spherical superheavy elements around element 114 and neutron-number $N=178$–184. Recent calculations emphasise the importance of the presumably stronger $Z=126$ proton-shell. A number of different approaches to obtain access to this region of rapidly diminishing cross sections can be envisaged. To find the optimum path towards these superheavy elements, a much better understanding is needed of all nuclear reactions leading to the synthesis of the heaviest elements.

"Hot fusion" reactions with light beams on actinide targets are studied at Dubna and GSI and have produced the most neutron-rich isotopes of element 106, 108 and 110. Fast chemical separation allowed half-life measurements in the range of seconds for $Z=106$, $^{265}$Sg and $^{266}$Sg.

At what point nuclear stability may finally limit the existence of chemical elements remains an open question, and hence presents a challenge to experiment and theory. The most important immediate goal is to reach the island of spherical superheavy elements at $Z \approx 114$ and $N=178$–184. However, no target-projectile combination of stable isotopes will directly lead to the centre of the island in a fusion-evaporation reaction.

**The long-term perspective** is the use of intense neutron-rich radioactive beams, mainly in combination with neutron-rich radioactive targets, to produce the most neutron-rich nuclei of heavy actinides, transactinides, and, ultimately, superheavy elements. With cross sections presumably ranging from fractions of a nanobarn to less than one picobarn, it is not obvious that intensity-limited radioactive beams may allow direct access to this region in the near future. However, nuclear reaction studies with radioactive beams can provide essential clues about how to proceed. Studies of the influence of just one important parameter at a time, like the fissility or the neutron-excess, are expected to shed much more light on the open questions about these mechanisms.
Recent studies have rejuvenated the entire field of chemical research of the transactinide elements which have now reached Seaborgium, \(Z=106\). It is the goal of these fast chemistry experiments to map out the architecture of the Periodic Table at its upper end. Increasing deviations from the periodicity of chemical properties have been predicted as a consequence of the increasingly strong Coulomb field of the highly-charged atomic nucleus (“relativistic effect”). For example, the non-Ta-like behaviour of Dubnium \((Z=105)\), and the contradicting behaviour of Seaborgium \((Z=106)\) which behaves like its lighter homologues, have demonstrated that the chemical properties of the heaviest elements cannot be reliably extrapolated from the trends observed in the lighter homologues.

Detailed nuclear and atomic spectroscopy on radioactive beams can significantly increase our knowledge of the heaviest elements. Storage of these beams in traps for further investigations, e.g. optical spectroscopy with modern laser techniques, would provide another big leap forward, but they also are an ultimate experimental challenge. Perhaps, chemical research may even approach the elusive island of spherical super-heavy nuclei around \(Z=114\) and \(N=178\) where theory predicts long half-lives. The key issue is the intensity of next generation radioactive beam facilities.

**Interplay between Nuclear Structure and Nuclear Reactions**

Many of the novel features of exotic nuclei are explored in reactions induced by radioactive beams. The analysis of the experiments poses important questions with regard to the reaction mechanisms with which the new degrees of freedom are excited. Of special importance for these studies are reactions involving elastic scattering, inelastic excitation and transfer reactions involving one or more nucleons. In addition, fusion and deep-inelastic reactions may provide new insights to pave the paths to the production of superheavy elements and to get access to more neutron-rich isotopes. Furthermore, fission provides ways to produce a wide variety of neutron rich nuclei.

**Elastic and inelastic scattering** induced by radioactive beams give information about the interaction potentials and the spatial extension of the projectile; they may also reveal directly the predicted existence of a neutron skin. For this purpose, it will also be interesting to study the angular distributions from inelastic reactions, since, via the nuclear-Coulomb interference, information about the mean square radius of neutron \(r_N^2\) and proton \(r_p^2\) densities may be obtained. Of particular interest in this field is the study of the energy dependence of the optical potential at energies close to the Coulomb barrier. It contains information about the open channels of the system under investigation. The presence of collective strength at low excitation energy, strongly excited by the Coulomb field, may give rise to large polarisations. This will considerably alter the shape and strength of both the real and imaginary parts of the optical potential over large distances. Because of the many open channels at low excitation energy and of the importance of the continuum, the standard analysis in terms of optical potentials and distorted wave Born approximation (DWBA) is not very suitable. To address these problems the use of complex coupled-channels codes, where elastic, inelastic and possibly transfer channels are treated on the same footing, may be needed.

**Coulomb excitation** provides a direct and clean way to obtain information on the properties of nuclei in their ground state and low-lying excited states. Coulomb excitation of the ions of the radioactive beams allows the study of the development of deformation in the vicinity of closed shells as has been recently demonstrated at GANIL in measurements of magnesium isotopes up to \(A=32\). Future exotic beams, obtained through post-acceleration with energies around the Coulomb barrier will allow for precision spectroscopy. The experimental information on giant resonances in exotic nuclei is at present marginal. Nevertheless they can be studied in inverse kinematics with secondary beams. Other standard tools for giant resonance studies, i.e. hadronic probes like \((p,p')\), \((a,a')\) or \((p,n)\) reactions can be adopted in principle, but they require new developments. Last but not least, inelastic electron scattering is a challenge,
as it would require an ion-electron collider, but it would provide a powerful probe.

One-nucleon transfer reactions are very good tools for the investigation of the nature of the single-particle level structure of interacting nuclei, while two-particle transfer can give information about pairing-correlations and thus provides insight into the nature of the pairing-interaction in the surface region.

![Graph showing cross sections for thallium and mercury isotopes](image)

Figure 5.2: Predicted cross sections for thallium and mercury isotopes by bombarding a $^{209}$Pb target with a stable $^{136}$Xe beam (yellow) or a neutron-rich $^{144}$Xe beam (red).

The multinucleon transfer process plays a very important role, both as a doorway mechanism towards deep-inelastic and fusion reactions, and may also prove to be one of the mechanisms for the production of very neutron rich nuclei which cannot be produced in the standard fusion-evaporation reactions, see 5.2.

Fusion reactions are the ideal tool for the production of superheavy elements, and the use of radioactive beams could substantially increase these possibilities. It is still an open question whether the presence of a neutron skin and of collective strength at low excitation energy could enhance considerably the yields for these reactions at energies below the Coulomb barrier or could be counterproductive. Fusion reactions, of course, must not be pursued only for the quest of superheavy elements but are very important in their own right. The outcome of fusion reactions is strongly influenced by the coupling to inelastic scattering and transfer channels. Studies of the energy dependence of these reactions, especially at energies close to the Coulomb barrier, can thus provide complementary information on the properties of these degrees of freedom in the new exotic nuclei.

Bi- or even multi-modal fission modes have been observed in the spontaneous fission of the most neutron-rich heavy actinides and light transactinides. Similar features have been seen in the fission of actinides at low excitation energy ($E^* \approx 12$ MeV) resulting from the excitation and decay of the giant dipole resonance (GDR); this opens a new field of studies with very interesting prospects. At GSI, cross sections were measured for the electromagnetic fission of a $^{238}$U target bombarded with 100 to 1000 MeV/u $^{208}$Pb beams and similarly for 600 to 1000 MeV/u $^{238}$U beams interacting with a variety of targets between Be and Pb. Cross sections of about 2 barn are reported for the heavy system at 1000 MeV/u. Secondary beams of radioactive, fissile heavy nuclei were produced by the fragmentation of a relativistic $^{238}$U-beam at the FRS, and their fission was studied in-flight in a secondary Pb target. These data give access to the fission barriers of highly fissile nuclei in the region of the $N=126$ neutron-shell and they are important for determining the end point of the astrophysical r-process and for the $\beta$-delayed fission process.

For neutron-rich isotopes far off stability, our knowledge of isomeric states is scarce. By means of delayed $\gamma$-ray correlation techniques, it has recently been possible at GANIL to identify more than 20 new, neutron-rich isomers in the fragmentation of $^{86}$Kr. Such fragmentation reactions will permit, for the SPIRAL project, post-accelerated isomeric beams. Another method for producing such beams could be through the excitation of the GDR with relativistic actinide beams on high $Z$-targets followed by neutron emission to fission isomers. The availability of isomeric beams will also be of interest for nuclear astrophysics.

The radioactive beams which are presently produced by the fragmentation facilities, or will be produced by the first generation ISOL+post-acceleration facilities, will already allow us to carry out experiments for a wide range of exotic nuclei, in particular for elastic and inelastic
scattering and Coulomb excitation. Extension of these experiments to even more exotic nuclei will require radioactive beams of substantially increased intensities with emphasis on neutron-rich species for fusion-evaporation reactions at energies around the Coulomb barrier.

5.2.2 Ground state properties

A substantial amount of information exists on the most basic properties of exotic nuclei in the ground state or at low excitation energies. Masses, moments, radii, spins, and decay modes have been studied for a large number of isotopes and are in general well known near stability. Further away our information becomes scarce and at the borderline of known nuclei often only a few decay properties are known. The fact that it is now realized that it is currently impossible to predict the exact limits of stability provides the forum for future exploration of the nuclear landscape (see figure 5.3). The employment of new techniques and the efforts devoted to the development of radioactive ion beams provide the possibility of extending experimental studies to more and more exotic regions, and to obtain detailed information on nuclei presently known only to exist.

**Nuclear Masses**

Masses contain basic information about nuclear structure: (i) Deviations of binding energies from the smooth trend given by a liquid-drop model directly reveal nuclear shell structure. (ii) Mass differences between odd and even nuclei show the strength of the pairing force. (iii) Departures from a smooth trend of the two-nucleon separation energies between shell closures reveal the onset of strong ground state deformations.

New accurate experimental mass data are essential for testing and improving theoretical models and will yield more reliable predictions of experimentally inaccessible isotopes, e.g. r-process path nuclei. For a general mapping, experimental accuracies of 100 keV and less are required. In some specific cases such as halo nuclei or nuclei used to test the conserved vector current hypothesis, accuracies better than 10 keV are mandatory.

Very far from stability Q-value measurements obtained from a reaction or a radioactive decay are often the first and only source of information on nuclear binding. An extension of the studies of halo nuclei towards heavier systems may be expected from reactions induced by the new radioactive beams. With regard to Q-values from decay studies, outstanding examples are isotopes along the proton drip-line and the new elements 110 to 112.

![Figure 5.3: Divergence of different mass predictions far from stability, underlining the need for mass measurements on exotic nuclei.](image)

Recently, direct measurements on radioactive isotopes have made important contributions. The renaissance of mass spectrometry is due to new time-of-flight and frequency measurement techniques, which are well adapted to radioactive ion beams.

Time-of-flight spectrometers like TOFI and SPEG have paved the way to access large regions of nuclei near the drip-lines. Applying a new concept, masses were measured for $A \approx 80$ iso-bars and 100Sn and the isotopes in its vicinity by means of the SARA and GANIL cyclotrons, respectively. New perspectives for very short-lived species will also arise from time-of-flight mass measurements at storage rings like the ESR.

With regard to frequency measurements, it has already been demonstrated (using a Schottky technique at the ESR) that cooler storage rings are a very powerful tool. Mass values of more than 100 neutron-deficient heavy isotopes were determined with an accuracy of
\( \delta m/m \approx 10^{-6} \) for half-lives as short as 10 s. Unprecedented accuracy, \( \delta m/m \approx 10^{-7} \), in direct mass measurements is today achieved with Penning traps. ISOLTRAP has already studied long isotopic chains for alkali, alkali earth and lanthanide elements. This method has the potential to be applied to essentially all nuclei with half-lives as short as 0.1 s. The new radiofrequency transmission spectrometer MIS- TRAL will provide a complementary technique at ISOL separators, to measure with similar accuracy, isotopes with half-lives down to milliseconds.

**Charge Radii and Moments**

The determination of nuclear charge radii and electromagnetic moments has been a domain of atomic spectroscopy at ISOL facilities via the measurement of the isotopic shifts and the hyperfine structure in optical transitions. A variety of newly developed laser spectroscopy techniques gave access to long isotopic chains for a large number of elements covering, in certain regions, even the isotonic dependence of nuclear radii and moments.

At ISOLDE, a novel detection scheme has allowed a systematic mapping of the radii around \( N=20 \) and \( N=28 \) by isotopic shift measurements on Ar, K, Ca nuclei. These data serve as an important test of shell model predictions for the sd and fp shell. Optical polarisation, combined with \( \beta \)-NMR provided access to the electric quadrupole moments of neutron rich sodium isotopes. The \( N=20 \) isotope \( ^{31}\text{Na} \) is now within immediate reach. For neutron deficient Sr and Kr nuclei, new isotope shift data are interpreted in terms of a core polarisation effect that drives the odd isotopes into a strong stable deformation. Recent investigations for refractory elements by laser-desorbed resonance ionisation spectroscopy have allowed the measurement of the isomeric and ground-state nuclear deformation of \( ^{184m}\text{Au} \). These promising developments at ISOLDE will be complemented by the laser spectroscopy program at IGISOL where refractory fission products are of particular interest.

Examples of laser spectroscopy applied to extreme nuclear states are the determination of spin, magnetic moment and deformation of the fission isomer \( ^{242f}\text{Am} \) and the study of the high spin isomers \( ^{178m}\text{Hf} \) and \( ^{177m}\text{Lu} \). In the future, optical spectroscopy of radioactive isotopes in magneto-optical traps may provide the means for atomic parity violation experiments.

In addition to the determination of radii and moments via atomic spectroscopy, nuclear orientation techniques provide complementary ways to obtain nuclear structure information. Besides optical pumping, experiments involving orientation at ISOL facilities have been achieved by developing implantation into low-temperature environments. In combination with moderate post-acceleration, the tilted foil method is thought to have a very important potential in the future. At higher energy, orientation is provided by the projectile fragmentation reaction itself. Pioneered in Japan for light neutron-rich nuclei, these promising first experiments have been started at other fragmentation facilities.

**Halos and Skins**

The halo structure, with its long tails in the density distribution and the strong clustering, has spurred a great deal of activity during the last few years. A better theoretical understanding has been obtained through work on few-body correlations and the halo degrees of freedom. Halo nuclei behave differently from normal nuclei both in beta decays and in essentially all types of nuclear reactions that have been attempted with them so far. They break up easily, and such processes are understood for one-neutron halos like \( ^{11}\text{Be} \), and progress is being made for two-neutron halos like \( ^{11}\text{Li} \). Open questions at the moment include how large the neutron-neutron correlations are for well-developed halos and how the structure develops as the drip-lines are approached. In addition, there is a real need to extend the understanding already obtained for nuclei with \( A=11 \) to other halo systems. Almost nothing is known about heavier halo-systems although several candidates exist and there are encouraging results on \( ^{19}\text{C} \).

To a large extent recent progress came from reaction experiments at 30–1000 MeV/u. Reaction cross sections and transverse momentum distributions, which were measured first are
Other progress for light nuclei in the last years has involved either nuclear astrophysics experiments or particle unbound systems, i.e. nuclei beyond the drip-line. Examples of the latter are the systems $^{10}\text{He}$, $^{10}\text{Li}$, $^{11}\text{N}$ and $^{12}\text{O}$. Their structure must be known if a coherent picture of the nuclear structure in this region is to emerge. Such a picture would be able to address questions like will the parity inversion seen in $^{11}\text{Be}$ show up in the related unbound systems $^{11}\text{N}$ and $^{10}\text{Li}$ and would be essential for understanding two-neutron halo nuclei since in all known candidates the corresponding “core plus one neutron” subsystems are unbound. The unbound nuclei can be created e.g. as part of the final state in break-up reactions of radioactive beams; this method can yield rather clean spectroscopic information as seen from the cases of $^{10}\text{He}$ and $^{10}\text{Li}$. In a similar way excited states in $^{11}\text{Li}$ have been probed.

Although developments in detection technology certainly are important, the progress in research on halo and skin systems is driven by the increase in beam intensities for (mainly) very neutron rich light nuclei. The constant progress towards higher intensities makes the future look very promising, in particular for skin nuclei where the relevant degrees of freedom are unknown. The biggest challenge for the field will be to find ways of producing the nuclei close to the neutron drip line above Na. This is a very ambitious challenge for the future.

### 5.2.3 Spectroscopy of exotic nuclei

Ground state proton decay clearly establishes the location of the proton drip-line. In addition, sensitivity to the orbital angular momentum of the unpaired proton can be used to assign shell structure even beyond the drip-line. So far proton radioactivity has been observed from odd-$Z$ nuclei in the two regions from $Z=51$–55 and $Z=69$–83. Studies of new examples from the “missing region” of light rare earth nuclei will be particularly interesting since this is where large deformation effects are expected. Another form of proton radioactivity — two proton radioactivity — has yet to be discovered but may possibly
be observed from even-Z nuclei bound to single proton emission. It is of interest for the possible observation of $^2$He clusters but will require increased yields of exotic nuclei since the drip-line for even-Z nuclei lies further from stability.

Exotic ions detected in a recoil spectrometer subsequently decaying by proton or alpha-emission can be used to tag the prompt gamma-rays generated in the reaction which produces such nuclei. This powerful new experimental method, developed at Daresbury, will enable detailed structure investigations to be undertaken at the proton drip-line, as exemplified by a recent study on light Po isotopes at the gas-filled recoil separator RITU at Jyväskylä.

Self-conjugate nuclei with $N = Z$ are of great interest due to the high degree of symmetry displayed between the proton and neutron degrees of freedom which provides a unique way to study the effective n-p interaction. For $A < 40$, such nuclei are $\beta$-stable, whereas for larger $A$, the Coulomb interaction drives the beta-stability line towards neutron-rich isotopes. Correspondingly, the $N = Z$ nuclei become increasingly unstable as the proton drip-line is approached. These nuclei exhibit a rich variety of phenomena, such as spherical - prolate - oblate shape coexistence, superdeformation, alignment of proton-neutron pairs and discrete line proton decay from highly excited states, with rapid changes of structure from one nucleus to the next providing a stringent testing ground for theoretical models. The doubly magic $N = Z$ nuclei $^{56}$Ni and $^{100}$Sn are fixpoints, where the prerequisites of any theoretical description, single particle energies and residual interaction, can be determined. In order to give one example, the nuclear binding energies are very sensitive to the residual interactions and correlations between weakly bound nucleons. In addition, the gamma-ray decay properties of self conjugate nuclei and Fermi and Gamov-Teller decay provide important information concerning the purity of isospin symmetry. As an example of work on mirror nuclei, a recent experiment concerning the mirror pair $^{49}$Mn, $^{49}$Cr shows a correlation between the alignment of the nucleons and the Coulomb energy differences between excited states. Also important are the precision beta-decay studies concerning the distribution of Gamov-Teller strength in the vicinity of $^{100}$Sn. Studies at GSI and ISOLDE have concentrated in particular on the structure of Cd, In and Sn nuclei in the range $N=50$ to $56$. Very promising is recent work at the GSI online mass separator, based on the combination of higher efficiency Ge detector arrays, such as the cluster cube, and total absorption gamma ray spectroscopy. These data show that the missing strength in Gamov-Teller beta-decay lies at higher energies than previously thought, and clearly indicate the Gamov-Teller resonance in beta-decay of heavy nuclei ($A \approx 100-150$) for the first time. Improved sensitivity and detection efficiency will allow us to exploit the large decay energy windows in beta decay far from stability to the full. Such studies can provide insight into the structure of halos, or information on highly excited states which subsequently undergo exotic multinucleonic decay processes.

Alpha and beta decay studies regain prime importance for studying nuclei near the drip-line. In addition, for proton-rich nuclei direct emission of protons may become possible. Alpha decay stucies of nuclei near the $Z=82$ and $N=Z=50$ shell closures provide detailed information, e.g. concerning shape coexistence and the onset of the double-shell closure.

Decay spectroscopy of neutron-rich nuclei will play an increasingly important role in providing a deeper understanding of highly asymmetric nuclear matter, e.g. testing the large scale shell model and other microscopic calculations for selected n-rich nuclei or by focusing on the evolution of nuclear structure between extreme deformations and double shell closures.

5.3 The Nuclear Response to Temperature and Angular Momentum

Over the next five years or so we expect a dramatic improvement in our knowledge of nuclear properties as a function of temperature and angular momentum.

In terms of the thermal response the emphasis is on how the elementary modes of excita-
tions are modified by the thermal environment. In this connection the transition from order to chaos, which is expected to occur at rather low temperatures, is of special interest. There will be further emphasis on multiple excitations of giant resonance modes starting with double and then triple excitation. The detail of how the excitation energy affects the coupling of the doorway and compound nuclear states for this basically cold excitation are of vital importance for our understanding of the effective interaction on the nuclear medium. When the giant dipole vibration is thermally excited on very elongated shapes, we expect that one of the components will be shifted to low energy and will strongly affect the E1 transitions in the decay cascades.

The focus of experiments on states with high angular momentum will be the observation of new types of exotic nuclear shape such as the hyperdeformed and triaxially superdeformed shapes. The experimental platform for such studies is provided by the new generation of γ-ray arrays together with their ancillary devices. Open questions such as the existence of "chiral-twin bands" and the very elongated shapes predicted in some light nuclei, the so-called alphachain states, should be answered. Increased sensitivity and energy resolution will allow us to pin down the symmetries revealed by regularities in rotational band spacings and the corresponding matrix elements. Progress here will require new theoretical insights. Understanding the tunnelling processes involved in the decay of nuclei with exotic shapes will require detailed measurements of the gamma-ray strength function.

5.3.1 Probing the nucleus at the limits of angular momentum and at extreme shapes

Rapidly rotating, highly excited nuclei are produced in nuclear reactions using beams of accelerated heavy ions. The response of the nucleus to the rotational stress gives rise to a wide variety of nuclear structure phenomena. Information on the properties and the behaviour of the nucleus is contained in a cascade of about thirty gamma-rays emitted as it deexcites from the highly excited state in which it was produced to the ground state. Improvements in high-resolution detector systems have steadily expanded the limits of what can be observed and new phenomena have been discovered leading to unexpected insights into the nature of the nucleus. The European Ge-detectors arrays NORDBALL, EUROGAM and GASP have significantly contributed in recent years to such progress and some of the challenging new ideas in this field await exploitation with EUROBALL.

One new phenomenon, recently discovered in spherical nuclei, takes the form of regular sequences of very enhanced magnetic dipole transitions. They were first observed in light-mass Pb and Bi isotopes, and then in nuclei in the mass 110 and 140 regions. This observation contradicts the familiar, intuitive idea that nuclei only show rotational bands if their mass distribution is deformed. In these cases it turns out to be a large magnetic dipole moment which breaks the symmetry and fixes a rotation angle. This moment rotates about the angular momentum axis and generates the strong magnetic radiation. Thus, "magnetic rotation" is, in addition to the familiar "electric rotation", a new manifestation of quantal rotation.

New types of rotational bands should also exist in nuclei with stable triaxial shapes, which are only just beginning to be explored. In the Lu isotopes large-deformation bands with sizeable triaxiality have been found. These nuclei are good candidates in which to search for the theoretically predicted "chiral-twin bands", where the triaxiality defines the direction of rotation.

Isomeric states have long been a prolific source of information about nuclear structure. For deformed nuclei the approximate conservation of the angular-momentum projection, K, on the symmetry axis leads to high-K isomers in regions where the Fermi surfaces lie high in the subshells. Recent research on K-isomers has provided new insight into shape tunnelling with a single-step decay from very large-K to low-K states, tilted rotation and the quenching of pairing correlations. The availability of radioactive beams will greatly extend the range of K-isomers.
that are accessible to study and promises to reveal examples of states with extreme numbers of quasi-particles. They will open up areas that are of interest to γ-ray lasers and to stellar nucleosynthesis.

The interplay between collective and single-particle motion may very well be demonstrated at the extreme high-spin end of rotational bands. When the angular momentum reaches that of the sum of the valence nucleons outside a closed shell or subshell, the nucleons align their spins and the mass distribution changes from prolate to oblate. This change may be sudden, leading to an abrupt band termination, or it may be smoother, resulting in a soft termination with a gradual change in the moments-of-inertia. Determining the expected decrease in collectivity in the spin 50 to 60 \( \hbar \) region is a challenging task even for the largest Ge-detector arrays such as EUROBALL.

Reproducing the existence of superdeformed nuclei at high spins has been one great success of the predictive power of nuclear mean field calculations. In the last five years the nucleus in its second (superdeformed) minimum has constituted a unique laboratory where we were able to test our ideas of the nuclear many-body problem. Indeed, a large body of detailed experimental information, including quadrupole moments, explicit single-particle configurations and moments-of-inertia, could be explained by mean field calculations based on the cranking formalism. On the other hand, superdeformed nuclei show some surprising and unexpected properties. The most challenging observation, not predicted by theory, has been the observation that rotational bands in neighbouring nuclei are almost identical in many cases, see figure 5.5.

At present, a global and consistent theory of identical bands is still lacking and the origin of the unexpected stability of moments-of-inertia remains the primary question to be investigated. A satisfactory solution to this problem could potentially lead to new insights into the structure of nuclei, to a better understanding of effective interactions, or even point to the exciting possibility that a hitherto unnoticed symmetry is realised in nuclei.

New types of symmetry have been invoked to explain another surprising discovery made in superdeformed nuclei, namely the oscillations of the moments-of-inertia of certain bands. The microscopic origin of the staggering in the γ-ray energies, see figure 5.5, is not yet understood. A possible explanation of the phenomenon involves the C\(_4\) point-group symmetry. The existence of other symmetries is still to be investigated.

One other recent major achievement in this field, made possible by the increased sensitivity of modern Ge-detector arrays, has been the finding, in a few cases in the mass \( A=190 \) region, of the transitions linking the SD minimum to the normal deformed states. This fixes the excitation energy and the angular momentum of the bands. Despite rapid progress in our studies of superdeformed states, many questions remain unresolved and new questions have been posed. One major challenge is to determine the excitation energies and spins of the superdeformed levels since, for example, there is not a single superdeformed band in the \( A=150 \) region for which these properties are known. Indeed, in this mass region the decay is so fragmented that even more powerful instruments than EUROBALL will be needed. Another major deficiency is that we have no detailed spectroscopy in the superdeformed potential well. The known excited SD bands are believed to correspond to particle or quasi-particle excitations, but the collective modes associated with states at large deformation are yet to be found. To shed more light on the cause of identical bands, it will be necessary to perform precise lifetime and g-factor measurements for such bands in various mass regions. The results forthcoming from powerful arrays such as EUROBALL will bring positive answers to some of these open questions.

At even higher spins, nuclear states with hyperdeformed shapes are predicted by improved mean field calculations. Here we are still in the situation with regard to superdeformation before 1986, i.e. there are signs of its presence from some ridge structure but no discrete rotational bands have been identified. Of course, the first step is to find such discrete bands and then establish their hyperdeformed charac-
Figure 5.5: Spectrum of $\gamma$-rays de-exciting superdeformed yrast states in $^{149}$Gd (top panel) and an excited superdeformed band in $^{148}$Gd (lower panel) which exhibit identical moments of inertia. Insert: difference in energy (compared to a smooth reference) between adjacent $\gamma$-ray lines as a function of their energy. The same “zig-zag” pattern is present in both bands.

...ter from lifetime measurements. We expect that they will be populated with an intensity at least one order-of-magnitude smaller than that of superdeformed bands, which means that they lie at the limits of sensitivity of the coming generation of large spectrometers. EUROBALL may provide an answer to the question of the existence of states with this exotic shape at high spins. Detailed studies of the properties of such exotic shapes will demand more sophisticated spectrometers of even greater sensitivity.

Very elongated shapes are also predicted in light nuclei. The most exotic examples involve chains of several $\alpha$ particles. To date their existence is deduced only from the observation of resonances in light symmetric systems in binary reaction channels. On the theoretical side, there are efforts to find more adequate microscopic descriptions of nuclear rotation including three-dimensional cranking models, generator co-ordinate projection methods, and large scale spherical shell model calculations. It will also be of primary importance to establish the role of time-odd components in the effective Hamiltonian/Lagrangian.

At lower angular momentum Coulomb excitation has been the main tool to probe the collective properties of stable nuclei. A recent example is the long sought observation of multi-phonon surface vibrations in strongly deformed nuclei; future investigations will have to concentrate on the elusiveness of two and higher phonon states and on the question of the fragmentation of the vibrational strength. Multi-nucleon transfer reactions with the multiple Coulomb excitation process provide the only promising tool for populating collective states in heavy transactinide nuclei and studying their behaviour at high angular momentum, which is important for our understanding of the shell structure of the heaviest elements.

With the advent of radioactive beams we will also be able to investigate in detail the collectivity of nuclei with exotic proton/neutron ratios. First Coulomb excitation studies confirmed definitely the sudden shape change in n-rich S isotopes and the fact that the semi-magic nucleus $^{32}$Mg is superdeformed. These findings encourage further investigations of the structure of these nuclei as well as of heavier isotopic chains to study the effect of the neutron excess on their shell structure (e.g. vanishing shell gaps). To gain access to higher spin states up to almost 20 $\hbar$, peripheral nuclear fragmentation reactions can be employed. Relativistic Coulomb excitation also leads to the population of the E1 giant dipole resonance, thus providing an unorthodox approach to the ground state quadrupole deformation of exotic nuclei via the splitting of the resonance. Alternatively, Coulomb excitation with low energy radioactive beams may be used to determine E3 octupole matrix elements of nuclei predicted to exhibit reflection asymmetry.

In addition, one should note that much of the information on the structure of very neutron-rich nuclei at higher excitations with spins up
to 14 h have come from the studies, which employ spontaneous fission sources and large Ge-detector arrays.

Most of the examples discussed in this section are associated with rather low production rates or can only be studied in reactions with low intensity radioactive projectiles. To overcome these difficulties, it is clear that a major effort has to be started right now to develop more sophisticated arrays if we are to make a significant advance both in efficiency and sensitivity.

5.3.2 Onset of Chaos in Warm Nuclei

Low lying nuclear states are characterised by quantum numbers, appropriate to the mean field description. Their decay modes are governed by selection rules based on these quantum numbers. A completely different situation is encountered at the rather modest excitation energy, corresponding to the neutron separation energy, of approximately 6 MeV. Random matrix theory, developed to describe the properties of these neutron resonance states, now constitutes the basis for the general concept of quantum chaos.

Nuclei at excitation energies between the regular ground-state region and the chaotic neutron resonance region can be characterised as warm. The temperature in this region is rather low, and the gross properties, such as the deformation, are governed by the shell structure. The transition between order and chaos occurs in this energy region, and it is of fundamental importance to find out where it occurs in energy, as well as to investigate experimentally the observable consequences of this transition.

The warm excitation energy region can be studied particularly well in deformed nuclei, where long sequences of rotational transitions proceed with only a little cooling. Already for the lowest lying rotational bands one encounters deviations from the rotating mean field description in terms of band interactions, leading to level repulsion as well as a bifurcation of the rotational strength. Statistical studies of nearest neighbour energy level distances of the lowest rotational bands, over the whole range of rare earth nuclei, have revealed the most Poisson-like distributions observed so far in nuclear physics. Recently the first small steps have been taken to obtain statistically sound information on the interactions between rotational bands above the yrast line. Systematic investigations at higher excitation energies require much more experimental information, and must await the next generation of detector systems.

The two-body interaction producing the coupling between the rotational bands has only a minor influence on the rotational pattern close to the yrast line, whereas it implies drastic changes in the appearance of the rotational transitions when going up in energy, due to the rapidly increasing level density. Statistical analysis of fluctuations in the experimental γ-ray spectra of decay cascades shows that the rotational strength function for most of the states is highly fragmented. In other words, the rotational motion is damped, that is the nucleus is rotating in excited states with a distribution of rotational frequencies, in analogy with phenomena in other areas of physics when a periodic motion is influenced by thermal fluctuations. For rare earth nuclei, it has been found that the first 20 to 40 states above the yrast line form regular rotational bands, and rotational damping sets in smoothly at around 1 MeV of excitation energy, see figure 5.6.

The rotational strength function contains microscopic information, for example about the alignment of angular momentum vectors and the interaction strength. An extreme situation of motional narrowing of such damping widths can in principle occur for rotational nuclei, if the intrinsic states are chaotic in nature, while at the same time the rotational strength is not fragmented. Such ergodic bands pose a challenge for future experiments.

Selection rules derived from the symmetries of the nuclear field are expected to gradually lose their validity with increasing excitation energy in the warm region. However, it has been suggested that the K quantum number, associated with the axial symmetry of a deformed nuclear shape, may only be partially broken around the neutron separation energy. This is based on the observation of gamma transitions from neutron
resonance states. A statistical analysis of unresolved spectra shows that it is hard to break the K quantum number in the excited bands despite the rapid rotation. States in the neutron resonance region in medium mass and heavy nuclei $S_n \cong 6$ MeV have chaotic properties. Systematic studies of neutron resonances in nuclei approaching the neutron drip line (where $S_n = 0$ MeV) might provide a tool to reveal the mechanism for the onset of chaos, and the dependence on excitation energy.

The recently discovered decay path out of some superdeformed bands displays a strong fragmentation into many final states in the normal deformed well. These observations support a picture in which the decay occurs via the coupling to a compound state, as illustrated in figure 5.7.

Here one has the advantage of having a well defined, superdeformed, regular state at considerable excitation energy embedded in thousands of normal deformed compound states. The coupling occurs via tunnelling with very small coupling matrix elements. Measuring the distribution of the decay strength provides a unique opportunity to study both the chaotic nature of the excited normal deformed states and the tunnelling process. Comparing superdeformed states in different mass regions one finds a considerable variation in the excitation energy, the angular momentum, and the barrier height as well as the structure content relative to the normal deformed states. This presents the prospect of investigating chaos-assisted tunnelling as well as the chaotic nature of the normal deformed states under different conditions. Both fission and the high spin cascades provide examples of dynamical processes, where the coupling between quantum chaos and dissipation may be investigated.

5.3.3 Giant Modes in Cold and Hot Nuclei

Since their discovery giant resonances have attracted much attention because of their fundamental nature. They provide insight into both the effective nucleon-nucleon interaction and other basic properties of nuclei, such as shape and compressibility. The giant monopole resonance (GMR) represents a compression oscillation, providing information about the compression modulus of infinite nuclear matter. While in heavy nuclei with $A > 100$ the GMR has been consistently found with its full energy-weighted sum rule (EWSR), only a part of the EWSR could be identified in light-mass nuclei, probably due to the fragmentation of the resonance strength. If this turns out to be generally true, it will imply a much higher centroid energy for this resonance than expected both on the basis of extrapolations from the $A > 100$ region and of the predictions of calculations with effective
interactions and with coupling to the continuum and to doorway states taken into account. These questions form a very lively experimental programme.

The isovector giant dipole resonance (GDR) can be excited in small angle inelastic scattering of isoscalar probes, e.g. 200 MeV $\alpha$-particles, via both the Coulomb and the nuclear interactions. The nuclear excitation matrix element is proportional to the neutron skin thickness, which occurs because of the different density distributions of protons and neutrons. In inverse kinematics, this offers a novel method of measuring the neutron skin thickness of unstable nuclei.

Giant resonances represent collective oscillations of all the nucleons in a nucleus. Such oscillations occur also in spin-isospin space, where protons and neutrons with spin-up and spin-down may move out of phase $\Delta S = 1$, $\Delta T = 1$. We are dealing with spin-isospin excitations, which are governed by the spin-isospin dependent part of the nucleon-nucleon (N-N) interaction in the nuclear medium. The Gamov-Teller resonance ($GT$, $\Delta L = 0$) has been well established in charge-exchange reactions. However, the mechanism responsible for the depletion of its strength has not been resolved satisfactorily as yet. Much less is known about the spin-flip $\Delta L = 1$ (SDR) and higher $\Delta L$ resonances. The use of polarised beams can be of great help in sorting out information on the different SDR excitations, as well as for the identification and delineation of the isovector M1 and $\Delta L = 1$ spin-flip modes in sd- and light fp-shell nuclei, which play a central role in the astrophysics context.

The study of the microscopic structure of a giant resonance requires measurements of nuclear decay to final hole states since it is a coherent superposition of $1p-1h$ states. Such studies will benefit greatly from the new accelerators at Groningen and Catania and from a range of new neutron and charged particle detection systems.

Giant Resonances can be understood as first oscillator quanta of the collective vibration. The recent discovery of the double GDR and GQR, the second oscillator quanta, has strengthened this picture, see figure 5.8. Rather different reaction mechanisms have been used to study multiphonon excitations: pion double-charge exchange, relativistic heavy-ion Coulomb scattering and medium-energy heavy-ion inelastic scattering. The existing data indicate that, to first order, these multiphonons can be thought of as consisting of independent phonons, although in several experiments the excitation cross section is about twice that implied by the independent phonon picture. If verified, this may point to small anharmonicities in the two-phonon structure or small non-linearities in the excitation process. A better theoretical understanding of the width and decay of the double GDR is still needed.

![Figure 5.8: Comparison of various experimental quantities $X$ for the two-phonon giant dipole resonance in $^{208}$Pb with those obtained in the harmonic limit $X^{harm}$. Results are shown for the resonance energy $E_0$, width $\Gamma$, integrated cross section $\sigma$ (averaged over all targets), decay branching ratio $T_{2\gamma}/T_n$ and neutron decay probability $T_n$. In all cases, the harmonic values $X^{harm}$ are obtained using the known values of the single GDR.](image)

When the $N/Z$ ratio differs appreciably from that in stable nuclei one expects exotic collective modes of excitation. This will be a very active area of research at the new radioactive beam facilities.

Giant resonances can be built on any nuclear state. The study of their decay provides information on nuclear structure at very high temperature and angular momentum. So far only the GDR built on excited states has been
studied; its characteristic γ-decay has been measured and the strength function extracted for many different reactions. This has provided information on how the nuclear shape evolves with temperature and angular momentum. A consistent picture emerges with a constant collisional damping width up to about 2 MeV per nucleon in excitation and a gradual weakening of the GDR strength above 3 MeV per nucleon. The explanation requires more refined measurements.

In fusion-fission reactions the total γ-yield from the initial state to the scission point is a measure of the relative partial decay widths, $\Gamma_\gamma/\Gamma_{fiss}$. Since γ-decay is mediated through the GDR, it can be used as an accurate clock to obtain the time evolution of the fission process. As for neutrons and charged particles, these studies have recently shown that the yield of pre-scission γ-rays is larger than expected on the basis of the Bohr-Wheeler description of the fission partial decay width, and could be explained by delaying the fission process through an increase in the viscosity of the nucleus. Evidence for a sharp onset of the nuclear viscosity as a function of the excitation energy has been reported for Th and Cf nuclei. A satisfactory theory is still lacking.

Furthermore, on the theoretical side, it is worthwhile remembering that isospin restoration in highly excited compound nuclei, predicted over 30 years ago, and found in recent dedicated experiments, still lacks a quantitative description.

5.4 Facilities and Instrumentation: How to proceed?

5.4.1 European Stable-Beam Facilities

For the experimental investigation of the structure of the atomic nucleus, European nuclear physicists presently rely on a network of essentially complementary facilities. These facilities provide high quality beams of ion species of almost all chemical elements with energies around and above the Coulomb barrier. Several accelerators have recently come into operation or were upgraded and offer an extended programme with stable beams:

At Legnaro (Italy), the 16 MV Tandem has been boosted by a superconducting LINAC providing heavy-ions with energies up to 20 MeV/u and masses up to A=100.

The new "Vivitron"-tandem at Strasbourg (France) presently feeds a broad spectroscopy programme based on up to 20 MV operation. In the longer term, the Vivitron design is aimed at operation with voltages around 25 MV.

The K=130 cyclotron at Jyväskylä (Finland) delivers intense and also rare isotopic beams ranging from protons to heavy-ions ($A < 100$) at energies above the Coulomb barrier.

The superconducting (K=600) AGOR cyclotron built by a joint Dutch-French group at Orsay (France) has been installed at the KVI Groningen (Netherlands), where the experimental programme is based on up to 200 MeV protons and 95 MeV/u heavy-ions, including polarized light ion beams.

Moreover, several regional accelerator facilities are in operation, which are concentrated — with the exception of the cyclotron in Warsaw (Poland) — mainly in western Europe. They provide beam time for various smaller scale nuclear structure programmes and the opportunity for extensive technological R&D as well as the basis for the training of students in experimental nuclear physics.

*It is strongly recommended to maintain and improve this network of stable beam facilities.*

5.4.2 European Radioactive Beam Facilities

Making radioactive beams

The two basic ways of making radioactive beams (see figure 5.9), offer unique research opportunities in nuclear physics and nuclear astrophysics. It is important to note that the two techniques address two different energy regimes with a very small overlap around 25 MeV/u. They thus are complementary.
The ISOL method, which was the first to be developed, uses the radioactive ions produced by the beams of a primary accelerator or by the neutrons from a nuclear reactor. The target/catcher arrangement stops the recoils and the activity is transported from there into an ion-source (diffusion, jet transport...). Chemical selectivity in the transfer process to the ion-source can be obtained by a suitable choice of the target material, of its operating temperature and of the “connection” to the source. A variety of ion source techniques is available today which can offer additional selectivity. Furthermore, much promising R&D is under way. After the extraction of the desired charge-state from the ion-source, and mass-separation, the radioactive species can be used for experiments at low energy (a few tens to a few hundreds of keV) or may be re-accelerated by a second accelerator. Louvain-la-Neuve is the first operational facility of this kind in the world. Here the radioactive beams are accelerated to energies of 0.65-5 MeV/u. Other projects, discussed in more detail below, will soon offer radioactive ion beams of a large variety of isotopes and/or with still higher energies.

Radioactive beams of energies above 20 MeV/u have so far been made at heavy-ion accelerators using in-flight separation of the recoils; a technique which relies on the forward focusing present in peripheral nuclear reactions. The concept of “fragment-separators” was pioneered with relativistic heavy ion-beams at Berkeley. The first dedicated spectrometer, “LISE”, was built for GANIL, followed by the construction of other large instruments, the “FRS” at GSI, “A1200” at MSU, and “RIPS” at RIKEN and, most recently the “SISSI” device at GANIL. At present, these fragment separators have a very heavy workload with some facilities investing up to 80% of their available primary beam time to secondary beam experiments.

**Fragmentation facilities**

At GSI (Germany), (LINAC + Synchrotron), the whole mass range of heavy ions is available with relativistic energies (up to 2 GeV/u), feeding the high-transmission fragment separator “FRS”. Storing and cooling the secondary beams by means of the “ESR” provides unique possibilities. Within 3 years the heavy-ion synchrotron SIS can be operated at its space charge limit, providing a considerable increase in intensity. Discussion of a long-term upgrade has started including a project for very intense relativistic heavy-ion beams.

GANIL (France), (two coupled K=380 cyclotrons), provides intermediate-energy heavy ion-beams up to 95 MeV/u. For rare, isotopically enriched beams world-record intensities are available and a further increase up to 6 kW of beam power will soon be made. Fragment separation is carried out with LISE (including a WIEN-filter for high purification) and SISSI (large solid angle).

The fragment separators ETNA and COMBAS will soon be commissioned at the K=800 cyclotron in Catania (Italy), and the K=450-630 cyclotron U400M Dubna (Russia), respectively.
ISOL facilities

ISOL-type beams produced bombarding thick targets with 1–2 GeV protons are available at ISOLDE/CERN. Radioactive ion beams from heavy ion reactions in thin targets are produced at the on-line mass separator at GSI (Germany) using a thermal ion source and at LISOL/Louvain-la-Neuve (Belgium) and at IGISOL/Jyväskylä (Finland) using ion guide systems.

The situation with regard to ISOL-laboratories featuring post-acceleration was summarised in 1993 in a detailed report from a NuPECC study group chaired by R.H. Siemssen. One important recommendation of this report was that a major R&D effort had to be completed before the technical case for the ultimate “2nd generation” facility could be made. This R&D, mostly of a complementary nature, would be assured by the “1st generation” facilities which are, from a strictly financial point of view, remarkably modest investments. In this sense, one may presently enumerate the following European facilities or projects.

Louvain-la-Neuve (Belgium) operates an intense low-energy proton driver (30 MeV, 500 µA) and a K=110 cyclotron post-accelerator. It will be complemented, in early 1998, by a new post-accelerator, the cyclotron CYCLONE 44. In this way, secondary beams close to stability, in the energy range for nuclear astrophysics (0.2 to 0.8 MeV/u) will become available with very good isobaric separation and an order of magnitude increase in intensity.

The SPIRAL facility at GANIL (France), is scheduled to begin operation in late 1998. The existing GANIL cyclotrons will be used as the “driver”, which allows a great variety of production reactions; the K=265 cyclotron CIME under construction will deliver exotic beams over a wide energy range (2–25 MeV/u), including nuclei far from the stability line.

REX-ISOLDE at CERN is also expected to be operational in 1998. This project relies on the long experience gathered at ISOLDE in the production of low energy beams of nuclei far from stability. A novel concept for post-acceleration, bunching and cooling in a Penning trap prior to charge-state breeding and injection into a linear accelerator, will initially provide ions covering the energy region up to 2 MeV/u.

The EXCYT project at Catania (Italy) will be operational around 1999, and will place special emphasis on secondary beams with well defined energies provided by the tandem post-accelerator; in the longer term a new 200 MeV proton driver is under consideration.

A project exists at Dubna (Russia), which relies on the two existing U400 cyclotrons.

The PIAFE programme at Grenoble (France) proposes the use of the reactor of the Institut von Laue-Langevin as a prolific source of very neutron-rich fission products made by the interaction of thermal neutrons with a 235U target. The first stage consists in the extraction of the secondary beams in the 1+ charge state; the second stage, including charge-state breeding and post-acceleration of these beams, is being studied in detail. The outcome of the R&D, associated with PIAFE will be of prime importance for a similar project at the FRM-II reactor at Munich (Germany); the reactor has been under construction since 1996.

Future opportunities in a world-wide context

The scheduled intensity up-grades at GSI and GANIL and the availability of beams from the “first-generation” ISOL post-accelerator facilities will ensure the leading position of European nuclear structure physics for the next five years.

Beyond this period, only a major step forward towards a next generation fragmentation facility will allow a thorough investigation of all the exciting aspects of exotic nuclei discussed earlier. European efforts will be in competition with the fragment beams from the MSU upgrade in the United States and the RIKEN project in Japan. The RIKEN project is particularly ambitious, adding to the present facility two superconducting cyclotrons, a booster synchrotron, three fragment separators, a double storage ring and an electron accelerator. The latter would
allow, inter alia, electron/exotic beam collisions and synchrotron-radiation excitation of atomic levels of exotic species.

Thus, there is an urgent need for concerted European action to explore all possibilities to maintain European leadership for radioactive fragment beams, e.g. by significantly upgrading GSI and/or GANIL.

In the same way, a major European effort is needed to develop second generation, ISOL based, post-acceleration facilities in order to maintain a leading position for Europe. It is important to note that the US DOE/NSF NSAC long-range plan "strongly recommends development of a cost-effective plan for a next generation ISOL-type facility and its construction when RHIC construction is complete". Furthermore, Japan plans to build such a facility at the intense driver accelerator (1GeV protons, 100μA) of the Japanese Hadron Project (JHP).

To maintain European leadership it is therefore vital to design and build a European "second-generation" RNB facility or facilities, capable of handling much higher activities for the radioactive nuclei produced in the primary target than is available at the "first-generation" facilities. As to the production method, detailed investigations have to be carried out on the characteristics of production by the intense primary beams, be it protons, deuterons, heavy ions, fast or slow neutrons. In this respect, e.g. the Radioactive Ion Source Test (RIST) project and the design study of the second generation SIR-IUS facility at the Rutherford-Appleton Laboratory (UK), where 0.1 mA of 800 MeV protons is available, are of interest. A second important initiative, supported by a European network (GANIL, Jyväskylä, Louvain-la-Neuve, KVI Groningen, Orsay) has been started to investigate the use of fast neutrons. Based on the R&D carried out at existing facilities, substantial technical developments will be required, to produce adequate targets and deal with their remote handling, their efficient coupling to the ion source and with the ion source systems themselves. Ultra-high current accelerators, developed in various contexts, e.g., for nuclear waste treatment, hybrid reactors and the European Spallation Source, will be very important. Design-studies for such high-current accelerators are now under way at Legnaro (Italy), at CERN (where they consider the re-use of the LEP cavities), and in France where the project IPHI has been launched.

As a first step towards European "second-generation" facilities we recommend the formation of a study group to consider the technical proposals, taking into account the European R&D efforts.

5.4.3 Special instrumentation

The continuing development of new instrumentation has been of vital importance to nuclear structure physics. Progress in research with exotic radioactive beams will be intimately linked to a continuous collaborative effort of the European laboratories concerned. Such co-ordinated R&D activities will be especially important to the key issues of recoil spectrograph, ion traps and storage devices and ultra-sensitive high-resolution detection systems. For example further progress in nuclear spectroscopy is intimately connected with the availability of high-resolution γ-ray detection systems. Only Ge-technology can provide suitable detectors for the next decade, although new solid state materials and other technologies, such as liquid Xe detectors, show promise of new, better instruments in the long run.

The new 4π EUROBALL array, presently installed at LNL Legnaro, constitutes today’s state-of-the-art γ-spectrometer for studies of reactions with high γ-ray multiplicities. It is optimised for the highest resolving power and its total photopeak efficiency is about $\varepsilon_{ph}=10\%$. Evolving from this project, segmented Ge-detectors are currently being developed. Segmented Cluster, segmented Clover and segmented true coaxial detectors will be employed in the MINIBALL, EXOGAM and MARS arrays, respectively, which are dedicated to studies of reactions with low multiplicities, in particular with radioactive beams. Given their low beam intensities maximum efficiency is of prime importance. High granularity of the individual de-
detectors is highly desirable because it allows the correction of the Doppler effects which determine the effective energy resolution in in-beam experiments. At the same time the detectors must be made insensitive to the increased radiation background introduced by the beam or the system must at least be capable of processing and rejecting its effects. All exotic beam facilities are scheduled, from the very beginning, to be used at a European level; collaboration in construction and use of these detection systems, due to their increased complexity, should also be at a European level. These arrays are planned to be available from 1998 on and will provide efficiencies well in excess of $\varepsilon_{ph}=10$

Concerning charged-particle detection, be it stand-alone or ancillary to a photon detection system, highly efficient arrays of detectors which cover most of the relevant solid angle of the reaction space are needed. There are two main areas for design considerations, detectors that surround the immediate reaction target and detectors for forward focused fragments. Ion implanted silicon detectors with thicknesses between 30–1000$\mu$m can now be manufactured with areas as large as 30 cm$^2$. Position sensitivity of 10$\mu$m is obtained by segmentation (“strips”). This allows us to select very weak reaction channels. Determining the direction of $\gamma$-emitting nuclei with such highly segmented detectors can be employed to reduce Doppler effects. For very rare events, one powerful technique is to use the 4$\pi$ detectors in coincidence with ejectiles analysed by means of a recoil spectrometer.

Neutron detectors are also powerful ancillary systems in connection with neutron emitting reaction channels. They are of vital importance for the study of neutron-rich nuclei, either to provide a trigger or for complete kinematics experiments. For these types of investigation good granularity with high overall efficiency is at a premium. The Franco-Belgian detector DE-MON is a good example of such an array, and the LAND detector at GSI presents the state-of-the-art for relativistic neutrons.

Complementary detector systems such as a high resolution 2$\pi$ electron-solenoid in conjunction with a 2$\pi$ Ge-shield are also important investments for future nuclear spectroscopy studies.

A requirement for many future experiments with rare exotic beams is high beam quality, i.e. low transverse and longitudinal emittance as well as the suppression of contaminants with very similar charge-to-mass ratios. A flexible variable time structure in the beam is also important. For these reasons the development of techniques for bunching, cooling, storing, and purification e.g. with lasers, traps, radiofrequency and buffer gas methods, are of vital importance for future success in nuclear physics and have potential applications in a number of different fields.

5.5 Concluding Recommendations

In recent times we have made significant progress in our understanding of nuclear structure. We have passed important milestones and we are now faced with challenging new questions. These questions address the properties of the nucleus at the limits of excitation energy, spin, isospin, and mass. The rapid development of highly efficient experimental techniques for the detection of photons, charged particles, and neutrons makes the investigation of the central issues of nuclear structure possible. These include questions related to extreme nuclear shapes and their evolution, and the influence of the thermal environment on both low-lying modes and giant modes of excitation.

Radioactive beam facilities will open the way to the study of new phenomena near the drip-lines, such as halo nuclei, neutron skins, neutron-proton pairing, the evolution of shell structure and exotic collective modes. At the same time, they will make it possible to test directly our ideas of how the chemical elements are created in stars. Great advance in our knowledge of the limits to the existence of nuclei is expected. Extrapolating from the recent observation of element 112, which lies near the predicted region of shell-stabilised nuclei, the synthesis of superheavy elements may come within reach of the next generation of radioactive beam
facilities.

To this end we recommend the following actions:

- If we are to exploit fully the detectors and other instruments created by recent major investments, and reach our scientific goals, nuclear structure studies rely on the continuing availability of accelerators providing high quality beams of stable and radioactive ions. Those accelerator laboratories which already form a European network of complementary facilities for nuclear research must be supported and further improved.

- Nuclear structure studies on nuclei at the limits of stability require accelerators with the highest possible luminosities and detectors of maximum efficiency. European collaborations involved in developing powerful new detector systems, the operation and construction of the first generation of radioactive beam facilities and R&D on high-power ion-sources and targets should be strongly supported.

- NuPECC should set up a study group to investigate and assess the main options for second generation radioactive beam facilities in Europe based on both the fragmentation and on the ISOL methods.

- Measures should be taken to strengthen and reinforce the theoretical physics community in order to mirror and support the thriving experimental programme. In particular, European universities must be committed to this goal by creating positions in theoretical nuclear physics. NuPECC should support the activities of the ECT* centre of Trento and help create adequate and more stable funding for it.
5. Nuclear Structure under Extreme Conditions of Isospin, Mass, Spin and Temperature
6. Nucleus-Nucleus Collisions and the Phase Transitions of Nuclear Matter

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6.1 Introduction

Nucleus-nucleus collisions are the tool to heat and/or compress atomic nuclei. The variation
of the collision energy and the system size allows to control the degree to which this happens.
In this chapter we will show how this tool can be used to study the phase diagram of nuclear
and hadronic matter over a wide range of parameters. A key factor is the availability of a
complement of accelerators that provide atomic nuclei with kinetic energies per nucleon ranging
from a few tens of MeV to several TeV.

In general, increasing the beam energy leads first to heating of the atomic nucleus, eventually,
as the beam energy is further increased, to temperatures such that the concept of a nucleus will
be replaced by that of a hot hadron gas and finally, at still higher beam energies, the concept
of a hadron gas will be replaced by that of a gas of the fundamental constituents of hadrons,
quarks and gluons. To set the scale, typical excitation energies for the three regimes can be characterised by temperatures (i) below 10 MeV, (ii) 10-100 MeV, and (iii) above 100-200 MeV.

The second relevant parameter to describe the phase diagram is a measure of the density
or compression. This will be expressed either in terms of the nucleon (or baryon) density, \( \rho \), in
units of ground state nuclear matter density \( \rho_0 \), or in terms of the baryochemical potential \( \mu_B \).

There may in fact be a third important degree of freedom, not present in atomic nu-

Figure 6.1: The low temperature, low density part of the phase diagram and the critical region of the liquid-gas phase transition

uclei, but possibly at somewhat higher excitation energies: strangeness. Since there is no evidence from experiment yet about the relevance of this degree of freedom, i.e. of hadronic
matter with significant strangeness (beyond hypernuclei, that is), this possibility shall only be
mentioned as a field for exploration.

The regions of interest of the phase diagram are shown in Figures 6.1 and 6.2.

At moderate beam energies of the order of a hundred MeV per nucleon the nucleus is heated
and compressed rather gently and may take during its decompression and cooling a path that
leads into the regions marked in yellow and orange in Figure 6.1. In these regions two phases
of nuclear matter coexist, the Fermi liquid and a cold gas of nucleons and light nuclei. The system can find itself in the spinodal region of negative pressure and it then breaks up (marked by the red star) into fragments of all sizes in a process called ‘multifragmentation’. The physics of the liquid-gas phase transition is discussed in the section 6.2.

When the beam kinetic energy is increased to a few hundred to 1000 MeV per nucleon nuclear matter is compressed to two or three times its normal value and heated to a few tens of MeV. A hot and dense hadron gas is generated who’s properties are dominated by the excitations of its original constituents, the nucleons. Meson production is starting to gain significance but the nucleon yield still dominates over the pions by typically one order of magnitude even at the top end of this energy range. This region is interesting because (i) to a very large degree the available energy is channelled into collective degrees of freedom during the cooling and expansion phase and (ii) it allows to sample the properties of hadrons embedded into a dense and hot baryonic medium. Section 6.3 deals with this energy range.

At still higher temperatures and baryon densities there is the boundary from hadron gas to the quark-gluon plasma (QGP), indicated by the blue line in Figure 6.2. Along the temperature axis this transition is predicted by Quantum Chromodynamics (QCD). Beyond the phase boundary confinement of quarks and gluons is lifted and chiral symmetry is restored. Present experiments create matter that is initially hot and very dense (up to 10 times normal nuclear matter density; indicated by the pink arrows) while at still higher beam energies achievable at the future colliders extreme heating of an essentially baryon free central region will dominate. Section 6.4 will address the current level of theoretical understanding as well as the present and future experimental possibilities to study the region of the QCD phase transition and the nature of the quark-gluon plasma.

To extract the physics outlined in this chapter requires, beyond the appropriate accelerator facilities, close collaboration between experiment and theory. The specific needs and opportunities connected to the theoretical investigation of this field are discussed in section 6.5.

6.2 From Nucleus to Nucleon Gas

The present activity in this field aims at the understanding of both the dynamical process leading to the formation of hot nuclei and the nature of the subsequent emission processes, from the lower excitation energies where evaporation or fission is observed up to excitation energies where the nucleus is vaporised into a gas of nucleons: typical excitation energies are therefore in the range between 1 and 20 MeV per nucleon.

The object of study is therefore a finite size quantum system and the large number of concepts which are used (thermodynamics, mechanical instabilities, percolation processes, etc.) bring this field into close contact with many other disciplines: It profits from them and will eventually contribute to extend their domain of
application. The introduction of quantum effects in these concepts is certainly one of the most challenging tasks of this field.

6.2.1 Multifragmentation and the liquid-gas phase transition of nuclear matter

One of the major axes of research in present day nuclear physics is the study of the decay of hot and compressed nuclear matter. Interestingly, in between the lower excitation energy regime of light particle evaporation and the high energy limit of complete vaporization, copious production of fragments is observed. This passage from a nuclear liquid to a nucleon gas, via the intermediate phenomenon of multifragmentation, has suggested numerous interpretations which extend from a thermodynamical approach to one that emphasises the dynamics of the process. The achievement of thermal and chemical equilibrium, the measurement of temperatures, densities and pressures, and the observation of a liquid-gas phase transition are only some amongst the most studied subjects.

One of the most striking results obtained in this domain are the recent publications related to the so-called nuclear caloric curve. These curves result from an independent measurement of both temperature $T$ (via measurement of ratios of isotopic yields) and excitation energy $E^*$ (via calorimetry) for a nuclear system. The upper part of Figure 6.3 shows the first of such measurements. One may notice the following features: i) at low energy a square root dependence of $T$ on $E^*$ as predicted for a Fermi gas, ii) a indication of a plateau possibly corresponding to a saturation of this temperature above an excitation energy of 3 MeV per nucleon, followed by iii) a linear rise whose slope is close to the one associated to an ideal gas. These features and a possible interpretation of the plateau in terms of a latent heat could represent a signal of the long sought liquid-gas phase transition.

In a similar measurement (lower part of Figure 6.3) temperatures deduced from a series of isotopic ratios differ among each other. These differences can be resolved by taking into account effects such as the population of excited states, secondary decays, and excluded volume.

The full lines in this figure show the predictions of a quantum statistical model where
Figure 6.4: Yields of fragments as a function of charge number for central collisions in intermediate energy dissipative collisions in comparison with predictions from a statistical model. Shown is the distribution of all fragments (left) and of the largest (Z1), 3rd largest (Z3) and 5th largest (Z5) fragment. Data from the Multics Coll. taken at MSU.

these effects are taken into account and where one assumes, for each excitation energy, an equilibrated state of given density and temperature. These results do not exhibit the simple features as shown in the upper part of Figure 6.3 and it is presently investigated to what extent the differences can be attributed to expansion effects, to the time dependence of the temperature of the system, and to the fact that different isotopes freeze out at different times.

Multifragmentation: Is equilibrium achieved? ...

One of the most significant and recent breakthroughs is the understanding that copious multifragmentation can indeed be achieved if low nuclear densities are reached as indicated in the phase diagram (Figure 6.1). Dynamical models show, e.g. for central collisions, that a first phase of compression is followed by expansion leading to the low density region where multifragmentation occurs. Using statistical models one finds significant fragmentation only if the densities decrease well below normal nuclear densities. Therefore, multifragmentation may be the experimental indicator that the critical/spinodal region in the phase diagram has been reached. It is, however, a subject of intense theoretical debate to what extent the fragmenting systems is really equilibrated or still has a 'memory' of the earlier phase.

The present hypothesis is that the velocity of the expansion which follows the primary compression depends on the symmetry of the colliding nuclei, on the incident velocity and on the impact parameter. If it is too small in order to reach sufficiently low densities the system reaches a turning point and shrinks back to its initial density (see second arrow in Figure 6.1).

If the initial expansion velocity is sufficiently large, low densities will be achieved and the medium will become unstable against volume fragmentation producing a large number of nucleons and fragments. This is, for such a scenario, the freeze-out configuration, comparable to the saddle point in nuclear fission. Before this freeze-out is reached, the dynamics of the expansion allows for the emission of nucleons and fragments (in small numbers) from the surface, thus cooling the system. The duration of the expansion, its velocity, the final densities reached before break-up and the amount of cooling are questions that are addressed and will be answered in the coming years.

A question of special interest arising from this scenario is if and when thermodynamical equilibrium is reached and to what extent the observed fragment yields (Z,A) and spectra are consistent with the statistical models applicable to such a situation.

A violent decompression phase or a strong thermal pressure will result in collective radial flow. Decoupling this flow from the thermal motion, the analysis of the production of intermediate mass fragments (IMF) by statistical codes give generally an accurate description as long as the size, the density and the excitation energy of the system at freeze-out are adjusted freely. This is shown in Figure 6.4 and can also
be seen in Figure 6.3. Whether the values obtained for this configuration are also consistent with the dynamics has to be verified for the various circumstances where multifragmentation is observed.

The evolution of the nuclear system formed depends on the initial condition of the system: impact parameter, relative velocity, mass asymmetry, total size of the system, etc.. This has led experimental studies to look at the evolution of systems formed under very different conditions: central collisions for symmetric systems where compression effects are important, peripheral collisions (or central collisions of asymmetric systems) for a more gentle heating of the nucleus. In most of these cases, copious multifragmentation is found, extending up to the vaporisation of the system. The large variety of beams accessible in Europe has clearly been a remarkable asset in these studies.

...Not necessarily

The thermodynamical picture for the evolution of hot nuclear matter is not the only one prevailing: such alays as dynamical effects, mechanical instability and percolative phenomena are suggested and it needs to be studied how they relate to the equilibrium picture.

It is, for example, of importance to point out that the freeze-out configurations are rather systematically located within the spinodal region (see Figure 6.1). In this region, any mechanical instabilities will rapidly grow and give rise to multifragmentation. It is therefore a challenge for future studies to disentangle which effect, mechanical instability or phase space, is predominant for the production of the IMFs.

The observation of a power law behaviour for the size distribution of the fragments has triggered a number of studies that have looked for evidence of critical behaviour. These analyses consider nuclear multifragmentation as one example of a critical phenomenon and attempts are made to extract from the data the related critical exponents. Comparison with percolative and liquid-gas systems show remarkable similarities. The existence of power law behaviour in fragment size distributions still has to be fully understood and progress in this type of critical analysis should eventually relate this nuclear phenomenon to the various universal classes of fragmentation, including thermodynamical processes.

Not all experimental situations populating a similar excitation energy range lead to copious multifragmentation: an example is the heating of nuclear matter with high energy anti-protons. In this case a strong reduction of IMF production is observed when comparing to ion beams. Assuming that anti-proton heating leads to a well defined equilibrated source, the production rates of IMFs observed are reproduced with statistical codes using as input parameter normal nuclear density. It is still necessary to understand the particular dynamical path followed by a system heated with anti-protons, i.e. what initial excitation energy is reached and how the system evolves to apparent equilibrium and statistical decay.

6.2.2 The dynamics of nuclear collisions

The above description of multifragmentation points to effects related to different dynamical paths followed by the system during the collision. A detailed understanding of the collision dynamics is therefore a priority. This is particularly the case for studies close to the Fermi energy where the transition between the low-energy mean field behaviour and the high energy domain where two body collisions prevail is expected to influence strongly the evolution of the system. Based on early data, dynamical models making use of BUU-LV equations have allowed the community to reach a significant understanding of the dynamical process. The more complete data collected with the new 4π detectors now becoming available impose more stringent constraints on the model and will provide an important testing ground for our present understanding of the dynamical evolution.

The early phase of the collisions

A unique probe of the Fermi energy domain is nuclear Bremsstrahlung \((E_\gamma \geq 30 \text{ MeV})\) which originates from the most energetic collisions between the nucleons in the reacting sys-
tem. These photons probe the initial phase of the reaction and are a direct manifestation of two-body dissipation. In contrast to hadrons, photons escape the collision zone without further interaction. Tracing the Bremsstrahlung spectra as function of impact parameter and comparing with transport calculations, for beam energies around 100 MeV per nucleon an initial compression corresponding to a maximum density of 1.5 $\rho_0$ is found. Despite the low yields two-photon correlations can be measured and the results reveal that, for the larger systems, Bremsstrahlung continues to be emitted beyond the first chance collisions. This means the photons can be used as a tracer of the dynamical evolution of the system. The relation between photon production and the expansion of the system leading eventually to multifragmentation, will be explored by correlating the Bremsstrahlung and multifragmentation signals in future experimental studies.

A unique path towards multifragmentation?

The latest experimental results confirm that a generalised overall binary reaction mechanism persists throughout the energy range of interest to multifragmentation studies. With increasing centrality an equilibrated central reaction volume is growing. This allows to identify and reconstruct projectile and target remnants whose sizes depend on the impact parameter of the collision and thus it appears to be possible to determine the size and the excitation energy of the reaction volume with high accuracy. An adequate investigation, both from experimental and theoretical points of view, of the collision dynamics of nuclei is strongly needed in order to understand the evolution of the multifragmentation phenomenon with impact parameter. The path leading towards a possible equilibrium state is governed by the far-from equilibrium dynamical evolution of the nuclear system, necessary to build a single excited piece of nuclear matter out of two cold colliding objects.

In order to achieve a quantitative description of the equilibrium conditions the contributions to the final observables from particles emitted prior to equilibrium need to be identified and separated. Experimentally they are accessible by systematically varying the dynamical conditions by exploiting various beam energies or projectile and target sizes. Especially the impact parameter dependence of these phenomena, which is of extreme importance for a correct determination of the size and excitation of the observed piece of (equilibrated) nuclear matter, deserves further studies.

A good understanding of the macroscopic, as well as microscopic nature of the interaction (for example how excitation energy and angular momentum are shared between the collision partners, what the fluctuations of such processes are, what the time scales,...) may be crucial to assess whether the values of excitation, temperature and density, which are the input for thermodynamical descriptions of multifragmentation are indeed consistent with the preceding dynamical path of the collision. Only a proper description of the dynamics as a function of impact parameter will give confidence in understanding this path.

Fragment production in peripheral reactions

Signals of a transition between mean field behaviour and two-body collisions dominance may have been seen, below 100 MeV per nucleon, in the observation of significant fragment production associated with peripheral collisions. An example is shown in Figure 6.5. Detailed studies of these fragments reveal that they originate from a region of velocity space intermediate between projectile and target. It is conjectured that they are produced at the contact zone between the colliding nuclei. Some of these fragments are supposed to break away very early from the system and could be associated with the formation of a neck, others are produced at a later stage from the fission of one of the nuclei but with a strong memory (angular orientation) of the collision dynamics.

The physics behind the production of these fragments (light particles are also seen) is potentially very interesting since the neck region could have quite different properties from those of the bulk. This could be an inroad for the study of nuclear matter at variable density and
Two main axes of questions have to be developed in the future: one is to achieve a proper measurement and understanding of temperatures and the second is to obtain time-dependent information on the dynamics of the reaction and on the fragment formation process.

A step towards the first goal should be achieved via a more precise measurement of isotope ratios and excited state populations. This requires the development of detectors with unit mass resolution for nuclei up to Z=20. A joint European program to manufacture these and to use them in a variety of experiments such as is the case presently for neutron and gamma detectors should be considered.

The second goal is more ambitious. Interesting time dependent signals have been obtained via the study of high energy gamma rays produced by Bremsstrahlung processes. This would involve the coupling of charged particle and gamma detectors with large efficiencies. Such a project is already developed in Italy, and an extension of this could be considered and driven by a European collaborative effort.

A more distant possibility is offered by the future availability of radioactive beams. The variation of the overall isospin ratio as well as the respective isospin ratio of the projectile, target and of the neck between them, opens up a new dimension in the study of nuclear matter. For this subject to develop, a significant theoretical effort must be undertaken in order to extract and define those signals that will carry the information after the cooling of the system. If this is warranted, a third generation of detectors may be called for.

**Accelerators** This program makes use of the wide variety of beams and energies provided at European laboratories in France, Germany, Italy, the Netherlands, Sweden, and at CERN.

- An important condition for the success of this field is the continued and easy access to the beams delivered by these institutions.

**Theory** A more precise description and understanding of these collisions requires a sustained effort and significant manpower. The in-
vestment made into the development of efficient detectors can only be fully exploited if it has its counterpart in the domain of theory. As an example, the necessary quantitative comparison between experimental data and model generated events requires the latter to be increased by several orders of magnitudes. Another necessary development is an improved implementation of quantum effects, of fluctuations and of finite size effects into the dynamical codes.

- A sustained effort in the development of theoretical models must accompany the incoming flux and analysis of experimental data. Besides sufficient manpower this also requires adequate computational infrastructure for the theoretical groups.

6.3 Hot and Dense Nuclear Matter and Hadron Gas

6.3.1 Compression, Expansion and the Equation of State

In central collisions of heavy nuclei with kinetic energies per nucleon of a few hundred MeV up to 1-2 GeV temperatures and densities are reached that clearly obliterate the concept of a hot nucleus. In this energy regime one rather studies the properties of hot and dense hadronic matter.

On a macroscopic level, this state is probably realised in nature in the interior of neutron stars and the cores of supernovae where the density, pressure and temperature of such a system are related by an equation of state. It emerges as a consequence of the interactions among the constituents in the limit that there is enough time and space in order to achieve an equilibrated state. The study of the equation of state in small and rapidly developing systems is a new and challenging field. Heavy ion reactions provide the possibility to address the question of the properties of extended strongly interacting hot hadronic matter in the laboratory.

In the energy regime discussed here the properties of the system arise chiefly from the interaction among the nucleons and their excitations: hadron production is just starting to become relevant and the pion to nucleon ratio reaches the 10% level at the 1 GeV/nucleon energy range. The hot hadron gas cools and expands until particles again freeze out, i.e. stop to interact strongly. In contrast to the situation discussed in the previous chapter this happens at conditions well removed from the critical liquid-gas phase transition region. Now the freeze-out is dominated by collective phenomena and this may, similarly as is the case for the macroscopic astronomical systems, again make the concept of an equation of state a useful approach.

How collective features form in hot and dense hadronic matter is a complicated process since many interesting and new effects can happen simultaneously: the NN-interaction might change in a surrounding medium, the effective masses of the constituents might change as a consequence of e.g. partial chiral symmetry restoration, and the constituents get excited into hadronic resonances.

To separate the various contributions is a demanding task that is however aided by systematically varying the incident energy and the system size since the different processes show different dependences on incident momentum, density and temperature. It also requires a close collaboration between theory and experiment.

It should also be emphasised that properties of hadronic matter at densities of a few times normal nuclear matter density need to be known accurately in order to quantitatively describe a possible phase transition into the QGP. This is the link to the physics described in the next subchapter. At the intermediate energies discussed here similar concepts and methods are used as for the highest energies, but the available information is already rather complete and thus can put constraints on the dynamical evolution of the reaction also relevant for the highest energies.

6.3.2 Status and Highlights

Substantial progress has been made in the phenomenological description of the hot and dense interaction zone generated in relativistic heavy ion collisions during the last couple of years. This is based on exclusive measurements of nu-
nucleons, pions, kaons and fragments that became available with a good characterisation of the collision geometry, i.e. the magnitude and direction of the impact parameter vector.

Collective Motion

![Figure 6.6: Excitation function of side flow shown in terms of the slope of the in-plane transverse momentum distribution with respect to rapidity at midrapidity. Data are from GSI, Bevalac, and AGS.](image)

At the low end of the energy range discussed here pion production is not yet relevant and the overall conditions can be inferred from the final state momentum space distributions of the nucleons and light nuclei. At finite impact parameters pronounced directional emission patterns are found in the reactions: (i) a sideward deflection of the forward and backward going nucleons in the reaction plane (sideflow) and (ii) an enhanced emission perpendicular to the reaction plane at centre-of-mass angles or midrapidity (squeeze-out). Both phenomena show a strong impact parameter and system size dependence that is being exploited in order to separate the contributions from individual nucleon-nucleon scatterings, the momentum dependence of the interaction and the mean field. Especially sensitive to the interplay of those processes is the so-called balance energy, where the flow vanishes as a consequence of the transition from an attractive to a repulsive nucleon-nucleon interaction. The balance energy, located at around beam ki-

netic energies per nucleon of 80-100 MeV, can also be viewed as the borderline for the onset of a hydrodynamical expansion and contains important information on the nuclear compressibility and the in-medium nucleon-nucleon cross sections. From the experimental data in conjunction with modern transport theories one is lead to the conclusion that a reduction of the scattering cross section is necessary due to the surrounding medium.

At slightly higher beam energies the collective effects are fully developed and most pronounced, as demonstrated in Figure 6.6. The sideward deflection extracted from the momentum distribution of nucleons projected into the reaction plane shows consistently from different experiments a broad maximum and almost plateau like behaviour up to a beam kinetic energy per nucleon of about 1 GeV. This is very much reminiscent of scaling properties of hydrodynamical calculations and supports the view that heavy ion reactions indeed lead to states that exhibit macroscopic properties of nuclear matter. The quantitative evaluation of the driving mechanism of the directed collective flow, i.e. the importance of nucleon-nucleon collisions versus the mean field, requires a systematic study of the excitation function of all flow observables and a careful comparison to transport theories. Equally important and interesting is the understanding of the onset and of the decline of the phenomenon since the disappearance of flow is indicative for a reduced pressure in the system as it is especially towards the higher energies expected for a different phase.

While the total energy that is observed in the directed motion only comprises a small fraction of the available energy it was realised in the systematic study of different ejectiles from various reactions that a surprisingly large fraction of the available energy is transformed into yet another collective degree of freedom. The spectra of the observed particles can only be explained by introducing a collective expansion scheme, in which all particles originate from a common velocity field that is superimposed to the (random) thermal motion. Since a large fraction of the available energy is bound in the collective motion this has the effect to lower the portion
assigned to thermal motion and thereby helps to explain the relatively high yields of light nuclei that favor low temperatures and entropies. Quantitatively, many groups have succeeded in describing the measured hadron spectra in terms of an expanding system that freezes out at a well-determined fixed temperature, a concept that seems to be applicable to the highest energies where even the phase boundary to the QGP might be reached as described in the next section.

A compilation of the model parameters, temperature and average transverse expansion velocity, is shown in Figure 6.7. At beam kinetic energies per nucleon below about 1 GeV and in central collisions for the heavier systems the expansion proceeds in an almost spherically symmetric fashion, while for higher incident energies and lighter mass systems larger longitudinal velocities are observed.

In those cases transverse momentum spectra at midrapidity have been used to extract the average transverse expansion velocity. Initially, in the domain of hadronic matter, the temperature as well as the expansion velocity rise almost linearly with the logarithm of the incident energy leading to quite exotic conditions where up to 50% of the available energy is transformed into collective kinetic energy. Note that for the highest beam energies shown (AGS and SPS data) the temperature values are deduced from an analysis of hadron yields and the spectra using these temperature values then yield the transverse flow velocities shown.

A detailed understanding of the expansion scheme is not achieved yet. That the simple picture of a sudden and common freeze-out needs to be refined is made evident by systematic differences arising from different analysis approaches (Figure 6.7): The temperatures derived in the analysis of spectra of light nuclei ($A < 20$) are systematically lower and the average flow velocities are larger as compared to results obtained from light particle ($A \leq 4$) data. The rather complete set of data available with a long lever arm in the ejectile masses is well suited to allow a more refined characterisation of the freeze-out scenario. Further studies and high statistics measurements should allow to determine the flow profile as it develops during the expansion together with the freeze-out conditions that might be very different from the static ones due to supersonic expansion with $\beta_{\text{expansion}} > v_{\text{sound}}$. A theory that reproduces the expansion properties is not at hand yet.

**Particle Production**

The thermodynamic conditions implied by the analysis of the spectra of light nuclei can be tested by the yields of produced particles. Below a beam kinetic energy of 2 A GeV produced mesons like pions and eta mesons originate almost exclusively from the decay of baryon resonances and can be used to determine the baryon resonance population at freeze-out. One finds that the $\Delta$-resonance is populated with 10 and 20% probability at 1 and 2/A GeV beam
energy and estimates a probability of 30% for the high density phase at 2 A GeV; this implies that one faces the formation of resonance matter and has to consider interactions among resonances. These baryon resonances become especially important for the production of heavier mesons since they serve as an energy reservoir in multiple collisions and enhance sub-threshold processes. Within the current accuracy all non-strange baryon and meson yields can be consistently accounted for both by dynamical calculations and by a thermal model including chemical equilibrium.

![Strange meson-production probability](image)

**Figure 6.8:** Near Threshold Meson Production Probabilities. Recent data from GSI and some older data from the Bevalac.

For strange mesons the situation looks quite different. Kaon ($K^+$) production rates are low with respect to phase space expectations based on non-strange mesons as can be seen from Figure 6.8. The production probability per participant nucleon is represented for the various mesons versus the fraction of the incident energy that is available for the meson production. While $\eta$-mesons follow the overall trend set by the pion data (solid line), kaons show a different near threshold production behaviour. The attempt to interpret their production probabilities shows a strong sensitivity to poorly known $NN \rightarrow NK^+\Lambda$ cross sections, to the $\Delta$-resonance population and to the equation of state. By constraining the first two points by new measurements of the elementary cross section and a consistent analysis of complete sets of pion data that are becoming available, there is a chance to isolate the effects of the equation of state.

One other observation from Figure 6.8 is remarkable and deserves further attention: in heavy ion collisions, at the same energy available to a colliding nucleon pair, antikaons ($K^-$) are produced with comparable yields as $K^+$. This is surprising, because the $K^-$ production cross section in nucleon-nucleon collisions at comparable incident energies is reduced by an order of magnitude with respect to $K^+$ production, and in addition the absorption process ($K^-N \rightarrow \Lambda\pi$) should further suppress the $K^-$ to $K^+$ ratio. To explain the similarity of the observed yields, a different mechanism may be needed for the strange meson production: theoretically, the difference could be a signal for the partial restoration of chiral symmetry since, at densities somewhat in excess of normal nuclear matter density, $K^-$ should experience a reduction of the mass while $K^-$ masses are changed very little. At twice ground state nuclear matter density, a value that is typically reached in heavy ion collisions at SIS energies, the $K^-$ meson might have lost already 50% of its mass. These exciting possibilities certainly demand further efforts. For example, the low momentum parts of the kaon spectra where in-medium effects are most pronounced have to be measured.

In general, experiments aimed at delineating the properties of vector mesons in hadronic matter are currently of great interest as they provide the opportunity to test predictions about the partial restoration of chiral symmetry: as one approaches the phase boundary between the "normal" hadronic world and the quark gluon plasma the masses of the vector mesons should be reduced because of the disappearance of the quark condensate. Precursor phenomena are already expected at normal nuclear matter density and should be enhanced at the temperatures and densities available at the SIS accelerator. With hadronic observables the $\phi$-meson can be reconstructed, while for the $\rho$ and $\omega$ mesons the mea-
measurement of dileptons is the mandatory choice to pursue this interesting question.

The dilepton spectrometer HADES is currently being built at GSI. This detector will combine dilepton mass resolutions of the order of 1% with a very large acceptance and hence be a unique facility for the investigation of the properties of (vector) mesons in hadronic matter, of dilepton production in pp and πp collisions, and of electromagnetic form factors of hadrons.

The experiments with the Hades facility will use the relativistic heavy ion beams (including protons and deuterons) from the SIS accelerator as well secondary beams from the pion beamline which is currently under construction at GSI. First experiments are planned for late 1998. The Hades collaboration presently consists of about 100 European physicists from 14 different institutions.

**Sideflow of Produced Particles**

Besides measuring the production yields of particles, some of the predictions based on the partial restoration of chiral symmetry can also be tested by the propagation properties of particles through their expanding environment. According to recent theoretical studies dropping masses are accompanied by modifications of the propagation of the particles through the nuclear medium. An example is shown in the lower part of Figure 6.9: various in-medium potentials for kaons were tested for their relevance to the finally observed sideward flow pattern. The sideflow of the nucleons offers the qualitative feature of pointing into the direction of the highest baryon density. Depending on their interaction particles can be either attracted towards this direction or repelled. Because of the associated production mechanism near threshold, the difference between \(^\Lambda\) and \(^{K^+}\) has to arise from differences in the rescattering and/or the potentials and thus probes the propagation process.

Data with enough accuracy to resolve the different theoretical assumptions start to emerge and thus open the possibility to cross check the ideas that are introduced for the understanding of the production process. Currently, within the framework of the chiral models the available \(^{K^+}\) data on the production and the flow seem to be consistent by requiring the balancing action of a scalar and a vector potential. Certainly more exclusive data with stronger flow effects in heavier systems will be needed to reach final conclusions. Measurements of \(^{K^-}\) flow will also help to clarify the situation.

**6.3.3 How to Proceed**

Summarising, the physics of hot and dense hadronic matter has received a large boost especially with the complement of detectors now operating at the SIS facility of GSI. The quest for the nuclear matter equation of state and more generally the search for the properties of
6.4 Hadronic Matter at High Energy Density, and the Search for the Quark-Gluon Plasma

6.4.1 Ultrarelativistic Nuclear Collisions

Astrophysical objects and processes, both connected with very early and very late phenomena in the cosmological evolution of strongly interacting matter, present an enormous challenge to modern nuclear and particle physics: can we recreate — in experiments carried out in the terrestrial laboratory — the conditions prevailing during the first microseconds of the cosmological expansion, or during the late stages of a violent supernova stellar implosion?

These investigations culminate, for the time being, in the CERN SPS which accelerates Pb nuclei to 158 GeV per nucleon to create extended "fireballs" of strongly interacting matter in head-on collisions of heavy nuclei. The systems created in these reactions reach energy densities close to the "critical" value of about 1.5 - 3 GeV/fm³, corresponding to temperatures of 150-190 MeV, where lattice QCD predicts the phase transition to a quark-gluon plasma as indicated in Figure 6.2.

Since its inception in 1986 at the AGS in Brookhaven and the SPS in CERN, the field of ultra-relativistic heavy ion physics has proceeded through three essential phases:

The initial round of 'exploratory' experiments has shown that appropriate detectors and analysis procedures can cope with the extreme particle densities produced in heavy ion collisions. They have shown that an extended, interacting and very dense system has been formed that differs in many observables from the more elementary hadron-hadron reactions investigated in the past. Falling short of striking discoveries, this phase has nevertheless provided a 'principle proof of feasibility' and has substantiated the expectation that heavy ion collisions are an appropriate tool to create equilibrium hadron matter and eventually the quark-gluon plasma.

The next phase was characterised by efforts to get a comprehensive and precise set of data
and to come to a quantitative theoretical understanding of the experimental results. A close and very effective interaction between theory and experiment has led to significant progress in identifying relevant ingredients and important microscopic processes. For example, a consistent and very intriguing picture emerged describing all relevant data on production of \( J/\Psi \) taken with hadrons and light ions in terms of initial and final state interactions involving partons, nascent coloured hadrons and physical quarkonium states.

The field is currently in its third, and most dramatic phase. The advent of a new generation of detectors, and most important, the availability of really heavy ion beams, has lead in the last 3 years to exciting new results.

A number of major experiments have taken part in the AGS Au-program and, more recently, in the SPS Pb-program, which started in late 1994. Most of them are second generation experiments, either completely new or upgraded versions of detectors operating previously with lighter ions. Built on the experience gained with the lighter silicon and sulphur beams, these experiments cope well with the total hadron multiplicity of about 2500 in an average central Pb+Pb collision (600 at the lower energy Au+Au collisions at the AGS), either by extreme granularity in case of the large acceptance detectors or by extreme selectivity for the experiments focusing on very specific signals. They address the most crucial questions: Are there indications for deconfinement, indications for chiral symmetry restoration, indications for equilibrium hadronic matter? The tantalising answer today to each of these questions seems to be: yes!

In the following, we will first describe progress in calculating the properties of the hadron-gas to QGP phase transition. Then we will turn to the current status of the experimental program and the understanding of the results. Finally, we give an outlook concerning the future of the field opening up with the 1999 startup of the BNL RHIC collider, and with the CERN LHC experiment ALICE in 2005.

### 6.4.2 The QCD Plasma State

For an equilibrated system of quarks and gluons, the computer simulation on a lattice of finite temperature QCD provides to date the most reliable theoretical information. Using this tool we can determine the equation of state for strongly interacting matter through ab-initio calculations. As a result, we know that hadronic matter will undergo a deconfinement transition at a certain critical temperature \( T_c \), closely accompanied by a second phase transition in which chiral symmetry is restored.

The results of present lattice QCD calculations are illustrated in Figure 6.10 which shows the temperature dependence of the Wilson loop \( L \) and the quark condensate \( \langle \bar{\Psi} \Psi \rangle \) along with the corresponding generalised susceptibilities \( \chi \). The quantity \( L \) is a measure of the free quark energy and thereby of the color mobility or color deconfinement. The sharp jump from very small values (low quark mobility) to large values occurs at the critical temperature corresponding to the deconfinement phase transition.

At exactly the same position the quark condensate, a measure for the quark mass acquired by spontaneous breaking of the chiral symmetry in low temperature QCD, drops steeply. These calculations indicate that quarks and, hence, hadrons loose their mass (except for the small current quark masses) at a critical temperature \( T_c \), a process called chiral symmetry restoration, and simultaneously acquire a finite free energy in the medium, resulting in a finite mobility corresponding to deconfinement. This interpretation is supported by a concurrent steep jump in the energy density (not illustrated). The susceptibilities shown as the red curves in Figure 6.10 are a measure of the fluctuations that characteristically are maximal in the vicinity of a phase transition.

To put the critical temperature on an absolute energy scale requires calibration of the lattice results by tying them e.g. to a physical hadron mass. The best calibration to date fixes the critical temperature to 150 MeV. Including systematic errors, the temperature range for \( T_c \) inferred from lattice QCD is between 150 MeV
and at most 200 MeV, as indicated in Figure 6.2 by the arrow.

All lattice QCD results obtained so far are valid for a system of vanishing baryon number density (baryochemical potential $\mu_B = 0$). To extend the knowledge of the hadron gas - quark-gluon plasma boundary into the domain of finite baryon number one needs to employ QCD inspired models (blue line in Figure 6.2).

Energy densities of about the required magnitude are indeed reached in the initial phase of central Pb+Pb collisions at the SPS together with baryon densities of up to 5 times nuclear matter density. However, the lattice calculations describe a stationary state whereas nuclear collisions are a typical example of a rapidly evolving system. Of equal importance as energy density are therefore lifetime and equilibration times in nuclear collisions. A very intense theoretical discussion is currently devoted to the question if thermal relaxation time scales are sufficiently small compared to the expansion time scale. However, the final answer concerning the creation of an equilibrated strongly interacting medium, of either partonic or a hadronic nature, can only be settled by experiment.

To fully explore the high-density regime simulations of the collision show that beam energies of a few tens of GeV per nucleon are optimal. Maximum densities are reached when the colliding nuclei still barely stop each other. A study of the chiral and deconfinement phase transitions along the density axis is complementary to studies at high energy density i.e. high temperature and is equally important for a full understanding of the nature of these phase transitions.

### 6.4.3 Status and Highlights

#### Hadron Production: Reaching Equilibrium Matter?

The bulk hadron production data reveal major aspects in which central nuclear collisions deviate from elementary pp, pA, or $e^+e^-$ collisions. Most markedly, in heavy ion collisions the abundance of strange particles are enhanced by a factor of two or more, depending on particle type, and the slopes of the momentum spectra change significantly and in a systematic way for different hadron species. The question whether these modifications are consistent with the formation of hadronic matter in thermodynamic equilibrium can be addressed by present experimental data at least for the late freeze-out stage when particles seize to interact strongly.

In a purely thermal system of hadrons, the
momentum) and 'chemical' (particle abundances) equilibrium is therefore fully determined by only a few independent parameters: $T$, $\mu_B$, and the expansion velocity profile.

Such a simple prescription seems to be indeed borne out by the data. This is illustrated in Fig. 6.11, which shows a comparison of measured particle ratios with predictions based on chemical equilibrium. Within the experimental accuracy, these ratios are in rather good agreement for a narrow temperature range of 160 to 180 MeV. Taking into account the yields of all available hadron ratios simultaneously, best agreement is reached for $T=165\pm10$ MeV and $\mu_B=175\pm10$ MeV. A similar analysis for the AGS data yields comparably good agreement with a somewhat lower temperature and a higher baryochemical potential. The resulting freeze-out points in the $T,\mu_B$ plane for both AGS and SPS are shown in Figure 6.2. The corresponding baryon densities are 2/3 and 1/3 of normal nuclear matter density, respectively.

Figure 6.11: Hadrochemical equilibrium model calculation of hadron yields which show a particularly strong sensitivity to the temperature of the system. In comparison are shown various experimental points from SPS experiments NA35, NA36, NA44, and WA85.

158AGeV/c Pb+Pb

Figure 6.12: Transverse mass spectra and inverse slope parameters of pions, kaons, protons and antiprotons near midrapidity from NA44 in central Pb+Pb collisions at 158 A GeV.

Figure 6.12 shows the transverse mass spectra of $\pi^+, K^+$ and $p, \bar{p}$ in central Pb+Pb collisions. The spectra appear near-exponential.
but the inverse slopes — which would naively be identified with emission temperatures in an expanding hadron gas — increase with hadron mass and reach up to about 300 MeV for baryons. While the slopes in pp reactions are independent of particle type, this so-called $m_T$ scaling is not observed in Pb+Pb collisions and, moreover, the inverse slope parameters far exceed the Hagedorn limit. However, the momentum spectra of all different particle species in Pb+Pb reactions are well described with a single temperature value of 165 MeV, consistent with the one derived from the analysis of particle ratios, if, in addition, a common flow velocity of $\beta_T \approx 0.3$ c is introduced. Recent data from experiment NA49 for two-pion Bose correlation functions confirm the existence of an ordered transverse, and in fact also longitudinal expansion velocity pattern. This provides an independent experimental tool to disentangle disordered (thermal) and ordered (expansion) motion. The temperature and flow velocity determined from momentum spectra at the AGS and SPS have been included in the systematics of Figure 6.7.

A large set of independent hadronic observables, i.e. momentum spectra, particle ratios and HBT correlation results seems to be consistent with a surprisingly simple picture of the late stages of heavy ion reactions: a dense hadronic system expanding in almost complete thermodynamical equilibrium, until a rapid freeze-out fixes momentum spectra and particle ratios to the finally observed values. In addition, the location of this freeze-out point in the temperature-density plane is located very close to the phase boundary. Model calculations that include a phase transition and follow abundances first of quarks and then of hadrons in the QGP phase, the mixed phase and the hadron phase via rate equations indicate in fact that the hadron yields are characteristic for the point when the system has completely converted into the hadronic phase. There is in fact the possibility that the spectral distributions are frozen in at a somewhat lower temperature than the particle yields. The spectra would then require an accordingly somewhat higher flow velocity.

$J/\Psi$ Production: A Signal for Deconfinement?

A decade ago the suggestion was made that suppression of charmonium production should be a signature of deconfinement. The heavy $c\bar{c}$ pair which, at the modest SPS central energy, can only be created in a hard parton collision in the initial phase of a nucleus-nucleus reaction serves as a probe of the surrounding high energy density matter. It was pointed out that the evolution of an initial $c\bar{c}$ pair towards its final $J/\Psi$ or $\Psi'$ hadronic state could be blocked if it is embedded in a state of deconfined quarks and gluons. In such a medium, Debye screening renders colour interactions short-ranged, thus breaking up the co-travelling $c\bar{c}$ pairs (like any other hadronic bound states), to end up in open charm $D, \bar{D}$ mesons. A suppression of the eventually observed $J/\Psi, \Psi'$ in central nuclear collisions was thus expected in a dynamical evolution proceeding via a deconfinement phase. Consequently one of the SPS experiments has concentrated on production of the $J/\Psi, \Psi'$ vector mesons.

![Figure 6.13: $J/\Psi$ production for proton, sulphur and lead induced collisions relative to the Drell-Yan yield as a function of the thickness $L$ of matter traversed on average. All data except central Pb+Pb are consistent with a suppression which is a single exponential function of $L$.](image)

Subsequently acquired data on $J/\Psi$ production in p+p, p+A and S+A collisions indeed ex-
hibited an increasing suppression as shown in Figure 6.13. The $J/\Psi$ yield of the various collision systems is plotted as its ratio to the continuum, the latter yield being independent of the course of the reaction dynamics. The horizontal scale represents the average path length $L$ traversed by the $c\bar{c}$ pair after its creation inside the target and projectile nuclei. This length thus also increases with the collision centrality. The normalised $J/\Psi$ yield drops exponentially, with the system size, up to and including central S-U collisions, finally to depart from this attenuation law in the new data gathered for Pb+Pb. The exponential attenuation, consistent with an absorption cross-section of about 6 mb, is seen today as resulting from the interaction between the nuclear medium and a pre-resonance state, a colored $c\bar{c}$-gluon configuration which evolves only later (and outside the nucleus) into the physical, color neutral $J/\Psi$ or $\Psi'$ hadron.

The final drop of the normalised $J/\Psi$ yield in Pb+Pb indicates a further suppression mechanism, setting in rather abruptly at a core energy density slightly above the one reached in central S-U. The tentative conclusion, debated intensely at present, is that we witness in these data the effect of a partonic medium which blocks the development of the $c\bar{c}$ pairs into hadrons.

**Low Mass Lepton Pairs: A Signal for Chiral Symmetry Restoration?**

Weakly interacting electromagnetic probes (photons or leptons) are a direct means of gaining information on the early dense and hot stages of the collision, as they leave the interaction volume without being altered by final state effects. In fact, since electromagnetic radiation is emitted throughout the evolution of the system it contains information from all stages of the dynamics cumulatively. While, so far, only upper limits exist for direct (thermal) photon production, recent data on lepton pairs show an unexpectedly large yield at low masses, below the $\varphi$ meson mass.

Figure 6.14 shows the electron pair mass spectrum observed in central S+Au collisions by NA45. The upper part summarises model calculations which include contributions from hadronic decays (shaded area) and from in-medium pion annihilation and Bremsstrahlung. An excess at $0.2 < m(e^+e^-) < 0.6$ remains unexplained. The lower panel exhibits perfect agreement with the data obtained in models which include in addition an in-medium reduction of the $\varphi$ and $\omega$ masses, driven by the high baryon density. A similar excess, consistent with the same model calculations, has been found in the $\mu^+\mu^-$ mass spectrum by NA34/3. Possible

![Figure 6.14: Di-electron invariant mass distribution measured by the NA45 (CERES) experiment in central S+Au collisions. In comparison to the data are shown calculations incorporating hadronic decays and effects expected for high pion densities (top) and calculations incorporating in addition a density dependent mass shift of the $\varphi$ and $\omega$ mesons.](image-url)
indications of in-medium modifications of kaons at high baryon density were already discussed in section 6.3 in connection with results from the GSI SIS.

In-medium modification of vector mesons, if experimentally confirmed by better statistics and resolution data, could be a direct consequence of the chiral symmetry transition at the phase boundary between hadronic matter and the QGP. The rapidly varying quark condensate (see Figure 6.10) should lead to changes in the properties of hadrons (masses, width) in the vicinity of the phase transition, which will be observable in the lepton mass spectrum for mesons decaying in the dense transition regime. This would indeed be a spectacular verification of the concept underlying the generation of light hadron masses in QCD. To establish this interpretation of the data a systematic variation of essential variables, baryon density and temperature, appears necessary. This will imply on the one hand running of the SPS at the lowest possible beam momentum of 30-40 GeV/c per nucleon. On the other hand, as discussed in the previous section, this physics will be addressed by the Hades experiment at the GSI SIS with heavy ions in the 2-3 GeV/c per nucleon range. It clearly would be desirable to fill the gap in between. But also the studies with nucleon and pion beams at the SIS will provide important information about in-medium modifications at nuclear matter density.

6.4.4 The Future of High Energy Heavy Ion Physics: The Collider Era

With the advent of two new colliding beam accelerators, a different regime of very high energy density and low baryon density, closer to the state of the early universe, will become accessible at RHIC (BNL) and LHC (CERN) a few years from now. RHIC and its four major experiments will offer the first step starting, in 1999, with Au+Au collisions at \( \sqrt{s} = 200 \text{ GeV} \) per colliding nucleon pair, an order of magnitude above what is currently available at the SPS. The LHC which will start operation in 2005 with Pb ions at a centre-of-mass energy of about 5.4 TeV per nucleon pair – almost thirty times the RHIC energy – will lead into a region comparable only to the highest energy cosmic ray events. While LHC is primarily a proton-proton collider it will feature a heavy ion program from day one with a single, dedicated ion experiment, ALICE (Figure 6.15).

Heavy ion collisions at the LHC are expected to provide a qualitatively different environment from existing accelerators by creating a very hot, and therefore more clearly detectable QGP via hard initial parton scatterings that can be calculated rather precisely. Extrapolating from present results, all parameters relevant to the formation of the QGP will be more favourable: the energy density, the size and lifetime of the system, and the relaxation times should all improve by a large factor, typically by an order of magnitude compared to Pb+Pb collisions at the SPS. We expect particle densities of several thousand per unit of rapidity, a freeze-out volume approaching 100,000 fm\(^3\), and an initial energy density more than one hundred times larger than the one of normal nuclear matter. The initial temperature is calculated to be close to 1000 MeV, as compared to a value of 400-500 MeV at RHIC and about 200 MeV at the SPS. The energy densities and temperatures at LHC should be far above the deconfinement threshold, allowing us to probe the QGP in its asymptotically free "ideal gas" form.

The analysis of extended strongly interacting matter at the LHC will move from the fixed target regime dominated by soft phenomena into a domain where the abundant formation of "mini-jets" with transverse momenta of a few GeV plays an essential role. The hard interaction between the primary partons will lead to a rapid production of further partons and thus a dense partonic medium. Perturbative QCD calculations can be used to construct and evaluate such parton interaction cascades; they indeed show the expected rapid rise towards thermalisation, on time scales considerably below 1 fm/c, to the extremely high initial temperatures mentioned.

In order to verify that a QGP was produced and to study its properties, we need probes sensitive to the earliest and hottest stages of the medium. Such probes must be hard enough to
resolve the short intrinsic length and time scales and they must be able to distinguish between dense confined and dense deconfined systems. Three such probes are currently known: Bound heavy quark resonances (quarkonia), hard jets, and thermal dileptons/photons. Only charmonia as deconfinement probes have been observed at the SPS as discussed above; for the others, higher incident energies appear necessary.

The deconfinement analysis of hot and dense matter must be extended to bottomium states, which are produced at sufficient rates at the LHC. The $\Upsilon$, with its very small radius, can be dissociated only at the highest energy density attainable at LHC (of order 30 GeV/fm$^3$), while the excited states $\Upsilon'$ and $\Upsilon''$ are comparable in radius with the charmonium resonances and will serve as important consistency checks.

Hard jets probe the produced medium through the energy loss of partons passing through dense matter. The theoretical aspects of this problem were recently studied in considerable detail, leading to substantial progress in the understanding of the relevant medium properties for energy loss in a QGP. In particular, the rate of energy loss was found to depend quite sensitively on the size of the medium. Furthermore, there now are indications that the energy loss in cold nuclear matter is much smaller than that in a hot QGP. Corresponding studies for the energy loss in a hot hadronic medium are still needed. The production and subsequent attenuation of fast partons will add a crucial new penetrating probe to diagnose the nature of the strongly interacting matter produced in heavy ion collisions.

The temperature of the primordial medium could be best determined through measurement of the spectra of real or virtual photons. Superimposed are the soft photons from the late
hadronic stage as well as the primary Drell-Yan or hard QCD photons. Whether there is a window in transverse momentum (around one to a few GeV) to actually measure such thermal dileptons or photons depends crucially on the density of the produced system; fortunately, conditions could be quite favorable at the high energy densities predicted at LHC.

Another unique feature of heavy-ion collisions at the LHC is the possibility to measure a large number of observables with very high accuracy on an event-by-event basis: impact parameter, multiplicity, particle ratios and spectra and, of particular importance, size and lifetime from interferometry. Single event analysis, currently pioneered by NA49 at the SPS, will become a precision tool at very high multiplicity. One of the important design considerations for the ALICE detector is to make full use of this opportunity. It will allow the study of correlations and non-statistical fluctuations which would otherwise be washed out when averaging over many events. Such fluctuations are, in general, associated with critical phenomena in the vicinity of a phase transition.

6.4.5 How to proceed

Given the exciting developments described above, but also their rather recent character, the future directions are clear.

The current SPS fixed target program is unique in the world, it addresses a well focused set of fundamental questions, it has entered an extremely productive phase and it has now to be brought to its full potential. With the exception of the low mass lepton pair measurements, statistics is in general not a problem. Rather the future program has to provide the answers to some well identified questions to settle the issues of equilibration, expansion dynamics and hydrodynamic behavior, anomalous J/Ψ suppression, and in-medium modifications of the vector mesons.

The continuation of the SPS program will include a low energy run around 40 GeV per nucleon which will increase the maximal baryon density but lower the energy density. This allows to play the two axes of the phase diagram against each other.

- It is of utmost importance that the SPS heavy ion program be brought to its full potential without any sacrifice so that the significant investment can be exploited. This program will require running for about five more years.

- The results becoming available may drive a request to continue the program beyond this period.

On the longer term, making use of the LHC for heavy ion collisions provides an unparalleled opportunity for exploring the physics of QCD matter in a qualitatively very different and unique region of extremely high energy density. The ALICE experiment is a common endeavor of the European high energy heavy ion community with smaller but growing participation from outside Europe. It is under preparation since 1990, has been approved in early 1997 by all relevant CERN committees and will be the future of the ultra-relativistic heavy ion program. Building a detector of the size and complexity required for LHC will be an unprecedented challenge for nuclear physics, and its successful completion will need the continued, strong and emphatic support and participation from the nuclear physics community in Europe.

- We strongly support, therefore, the construction of LHC at the earliest possible time.

- The realisation of ALICE at day one of LHC running is the highest future priority and will require the full commitment of the community and its resources.

- The time scale of LHC vis-a-vis RHIC allows for a limited European participation in RHIC. It clearly would be beneficial to participate in the science and further the development of new technologies. This would likely be reciprocated by the participation of US groups in ALICE.
6.5 Theory

In theoretical studies of matter at extreme temperatures and densities, a common problem has emerged in recent years. The evaluation of large and complex systems of many degrees of freedom becomes possible only if theorists have access to high performance computational facilities and sufficient manpower. For the experimental investigation in this field, considerable investments are being made and will be made in Europe during the next decade. To assure that the resulting data indeed lead to the anticipated increase in our understanding, a commensurate support must be provided for the associated theoretical work.

In particular, this requires:

- a European facility for large-scale computing in the field;
- support for the manpower and the training of young theorists and for their needed computational equipment;
- a European forum for the crucial interchange between theory and experiment.

6.5.1 Large-Scale Computing

The fundamental thermodynamics of strong interactions can only be evaluated by computer simulation of lattice QCD at finite temperature and density. These studies form the basis for the experimental investigation of hot and dense strongly interacting matter. They require extensive numerical work on the most powerful high performance computers, and if in Europe such facilities are not available and maintained at the latest technological level, basic research in this field is no longer possible here.

The theoretical analysis and the simulation of events produced in high energy nuclear collisions requires the processing of unprecedented amounts of data and therefore advances in computer technology, analysis algorithms, and access to large computational facilities. It is also necessary to facilitate the access of theory groups to such facilities and to provide sufficient up-to-date computing power for their needs.

In both areas, there exists a broad and experienced European community able to solve the mentioned problems, if it is provided with the necessary computational infrastructure. To remain internationally competitive, it is essential to establish a dedicated European facility of the highest technological standard to address the study of complex systems in nuclear physics. Such a facility should be operated by a group experienced in large scale computational physics and made accessible through high speed networks to all European groups in the field.

6.5.2 Human Resources

The character of nuclear physics experiments has changed with the advent of the so-called 4π detectors which measure for each event up to several thousand observables. Equally important, the physics questions have changed. Some of the questions addressed in experiments, like the study of the equation of state, of in medium properties of hadrons, of many-body reaction mechanisms, or of multifragmentation can only be answered by studying multi-particle correlations. Very man-power intensive work is necessary to achieve the interesting physics results. This not yet generally honoured by the funding agencies. Adequate support for this task is strongly recommended.

6.5.3 The ECT* in Trento

The highly excited nuclear, hadronic, or quark-gluon matter created in heavy-ion collisions requires to deal with complex dynamical many-body systems whose theoretical description is highly demanding both with respect to human resources and computing power. Experience has shown that a quantitive understanding of the observed phenomena cannot be achieved without a comprehensive exchange of even technical information between experimentalists and theorists. For this purpose we support the idea of a European Centre of Theoretical Nuclear Physics which can serve as a clearing house for new theoretical ideas and stimulate experimental and theoretical progress by initiating quantitative comparisons between theory and data. The ECT at Trento, founded in 1993, has been
quite successful in playing such a role. It is considered necessary to provide a broader basis of the funding preferably on a European level.
7. Quark and Hadron Dynamics

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7.1 Introduction

Up to now, the focus of nuclear physics research has mostly been on the description of nuclei at the scale of 1 fermi in terms of colourless particles, nucleons and mesons. At this scale, quarks and gluons are confined within the nucleons, and nuclei may be described as interacting systems of many non-relativistic nucleons. High energy experiments have, however, revealed interesting dynamics at much shorter distance scales, where hadrons are composed of interacting quarks and gluons.

In the past two decades, Quantum Chromo Dynamics (QCD) has emerged as the theory for the strong force with quarks and gluons as the building blocks of nuclear matter at large densities and high temperatures. One of the most exciting challenges for nuclear physics is the study of the non-perturbative regime of QCD. It is this regime which is relevant for understanding how the elementary fields of QCD – quarks and gluons – build up particles such as protons and neutrons. A basic theoretical difficulty is the non-existence of asymptotic, isolated, coloured objects. This is a feature of the richness of the vacuum structure of QCD. Understanding the different QCD phases and the transitions among them is the challenge of the modern study of strong interactions. At low energy, chiral symmetry can be used to build an effective theory of hadron interactions. At higher energies, the parton model uses non-perturbative quark and gluon distributions to describe hadronic scattering processes.

7.2 Nuclear Structure

7.2.1 Many Body Problem

Figure 7.1: Momentum distribution of protons in $^{208}$Pb. The solid curve is a mean-field prediction.

The last decade has been marked by a remarkable interplay between many-body theory and high precision electron scattering experiments. The nuclear response has been measured at high momentum and into the continuum. Fig. 7.1 represents the momentum distribution of protons in $^{208}$Pb measured at NIKHEF. The data have been extended to 500 MeV/c where the effect of correlations is clearly seen at high nucleon momentum. The partial occupancy of mean-field orbits ($\approx 70\%$) is one of the cleanest signatures of nucleon-nucleon correlations. The virtual collision of two nucleons to unoccupied states produces a depletion of the states below the Fermi energy and populates the states above. The central problem is now to understand the effect of correlations on nucleon distributions and other observables. High resolu-
tion experiments using the $eA \rightarrow e'p(A-1)$ and $eA \rightarrow e'pp(A-2)$ reactions will allow us to probe very high momentum components and separate the longitudinal and transverse components of the nuclear response. Clear evidence for the direct knock-out of a correlated proton pair in a heavy nucleus has been observed in the reaction $^{16}\text{O}(e,e'pp)$ at NIKHEF. Using large solid angle detectors, the angular correlation between the two emitted protons was determined with sufficient precision to extract information on the relative wave function of a proton pair moving in the $1p$ shell in $^{16}\text{O}$. The measured energy spectrum up to 20 MeV and momentum distributions are clear evidence for the direct knock-out of pp pairs in the $^1s$ and $^3p$ relative states (Fig.7.2). Such results demonstrate that high luminosity and high resolution, continuous beam electron accelerators will be able to extract a wealth of new information on short-range nucleon-nucleon interactions in nuclei.

![Figure 7.2: Excitation spectrum measured in the $^{16}\text{O}(e,e'pp)$ reaction. The solid curve is a fit to the data containing the following contributions: $^1S$ (dashed), $^1P$ (dotted) and continuum (dot-dashed).](image)

For few-nucleon systems, calculations that take into account realistic nucleon-nucleon interactions and mesonic degrees of freedom have made impressive progress, particularly for continuum states. Future experiments involving polarised electrons and polarised nuclei, will allow experiments to unravel the spin structure of light nuclei.

Elucidating the short-distance structure of nuclei will be a topic of special interest. One will study in particular how nucleon properties are affected by the nuclear medium. The study of the Coulomb sum-rule in quasi-free inclusive electron scattering shows that down to distances of 0.5 fm, nucleons in their ground state are little affected by the nuclear medium. At shorter distances, nucleons can no longer be considered as rigid objects, and one would like to understand the effect of the nuclear medium on their quark structure.

### 7.2.2 Hypernuclei.

The study of hypernuclear structure provides an original alternative approach to the nuclear many body problem. A striking example is the existence of deeply bound states of $\Lambda$'s in a nucleus. The Pauli exclusion principle does not prevent a $\Lambda$ from occupying a deeply lying shell already filled with nucleons. Hypernuclei also represent a unique laboratory for the study of the weak interaction reaction $\Lambda N \rightarrow NN$, that can occur only in nuclear matter and not in vacuum. Meson-exchange and quark model predictions are quite different for the relative strengths of the weak $\Lambda$-neutron and $\Lambda$-proton interactions, but the present data, do not allow a significant test due to their low statistics and large systematic errors. Hypernuclear initial states and nuclear final states may be used as a filter for selecting the quantum numbers in the reaction usually referred to as non-mesonic decays of hypernuclei.

In the next five years the completion of two new major experimental facilities will enlarge the present scenario. The FINUDA experiment at DAΦNE (Frascati), will exploit the low-energy (16 MeV) $K^-$ from $\phi$ decay, background free and tagged, to produce abundantly $\Lambda$ - hypernuclei by the $(K^-_{\text{HF}}, \pi^-)$ reaction on several nuclear targets. The momentum transfer involved in the reaction is such that all the spectrum of allowed hypernuclear states will be populated. The good energy resolution will allow a substantial step forward in spectroscopy. The transparent structure of the detector will allow one an unprecedented step forward in the study of the non-mesonic decay of hypernuclei. An extensive research programme on hypernu-
clear physics with a remarkable energy resolution is planned at CEBAF (Jefferson Lab) using the \((e,e'K^+)^+\) reaction. The University of Mainz proposes an energy upgrade of MAMI to 1.5 GeV that will also give access to strangeness production. One hopes to disentangle the doublets of states expected by the weak spin-orbit interaction of the \(\Lambda\) and to determine their form factors.

### 7.3 Hadron Dynamics

#### 7.3.1 Chiral Dynamics

Chiral perturbation theory (CHPT) provides a framework for non-perturbative calculations in the long wave length limit of QCD. Within this framework one would like to understand the mechanism of the spontaneous violation of the approximate chiral symmetry of QCD in the light quark sector at low energies. While it is believed that this mechanism is similar to that in ferromagnets below the Curie temperature, no ab initio QCD calculation has hitherto been done, which would show the quark pair condensation in the vacuum. CHPT leads to self-consistent relations between various physical processes which have to be fulfilled, if the spontaneous chiral symmetry breaking occurs as believed. Combined with precise measurements, one will be able to pin down the value of the pertinent order parameter \(B\).

Another major goal of theory is to understand the explicit chiral symmetry breaking due to the small but finite light quark masses. CHPT offers an important tool for the determination of the ratios of these fundamental parameters of the standard model. While these ratios can be inferred from the meson sector (e.g. from the ratios of the Goldstone boson masses), the nucleon (baryon) sector can give important additional bounds. Furthermore, as stressed by Weinberg already in 1979, for the two flavour sector of the light \(u\) and \(d\) quarks, \(G\)-parity forbids isospin-violating strong interaction terms \(\sim m_d - m_u\) to leading order in the pion Lagrangian, but allows such leading terms in the pion–nucleon sector. Therefore, precise measurements of elastic pion–nucleon scattering and single pion photoproduction (in the corresponding threshold regions) would sharpen the understanding of the fundamental question of isospin violation in the strong interactions. An extensive program of high precision measurements is in progress at MAMI. The measurement of \(\pi^0\) production off protons has been already performed. Fig. 7.3 represents the data for the amplitude of \(\pi^0\) photoproduction at threshold compared to the chiral perturbation prediction.

![Figure 7.3: Amplitude of photoproduction of \(\pi^0\) at threshold.](image)

Similarly, the precise pionic atom measurements to determine the \(S\)-wave \(\pi N\) scattering lengths at PSI clearly show the relevance of chiral pion loops and when supplemented with a full scale calculation of virtual photons can lead to bounds on \(m_d - m_u\). Such precision measurements at low energies are truly quantitative tests of QCD. Such studies also include pion electroproduction as performed and planned at NIKHEF and MAMI, which allow to pin down the nucleon axial radius and lead to detailed tests of CHPT predictions. For that, L/T separations and polarisation observables are a must.
The DIRAC experiment at CERN also aims at this goal by measuring the lifetime of the pionic atom $\pi^+\pi^-$. The inclusion of the strange quark is a challenge since the strange quark mass is much larger than $m_{u,d}$. Calculations indicate the usefulness of CHPT in the threshold region, but precise data are needed to test the predictions. DAΦNE will produce large numbers of $K$-mesons and also $\eta, \eta'$ mesons. CELSIUS and the 4π WASA detector will provide an $\eta$ factory. Chiral symmetry makes detailed predictions for decays of these mesons. Precise data in hadronic processes like threshold single and double meson production in $pp$ collisions close to threshold will be available from COSY and CELSIUS.

7.3.2 Hadrons in the Nuclear Medium

Hadronic degrees of freedom appear in an effective way in the nuclear medium. Significant modifications are predicted by QCD-inspired models for the density and temperature regimes encountered in heavy ion reactions. Sizeable mass changes ($\approx 10 - 20\%$) are predicted already at normal nuclear matter densities and should be accessible experimentally in pion- or photon-induced reactions on nuclei. These modifications of hadron properties may be associated with a decrease in the chiral condensate with increasing density and temperature. They could be a precursor phenomenon for chiral symmetry restoration.

The properties of baryon resonances in nuclei at normal density have recently been systematically studied at Frascati, Mainz and Bonn in photoabsorption experiments which show significant medium effects. While the $\Delta$ is only slightly distorted, higher excited nucleon states, in the second and third resonance regime, appear to be washed out. Moreover, in the region above 0.6 GeV the value of the absorption cross section per nucleon is significantly reduced as compared to the free nucleon value (Fig.7.4). Fermi motion and Pauli blocking are unable to reproduce the strong damping of the total photoabsorption cross section in nuclei. A strong interaction between nucleon resonances and the nucleus is able to reproduce the data only in a limited energy range. The microscopic origin of this effect is not understood. Several explanations have been proposed such as partial deconfinement of quarks in nuclei or the onset of shadowing effects at low energy, or the decrease of vector meson masses inside nuclei. As experimentally shown in the photoproduction of $\eta$-mesons off nuclei, some resonances like the $S_{11}(1535)$ seem, however, to preserve their identity in the nuclear medium, probably due to their specific structure.

A new approach to medium modifications of baryon resonances is provided by the excitation of the $\Delta$-resonance in reactions as e.g. $^{12}\text{C}(e,e'p\pi)^{11}\text{C}_{gs}$ reaction. Measurement of this reaction with the MAMI three-spectrometer setup shows a cross section enhancement for high initial momenta of the struck nucleon in comparison to the $^{12}\text{C}(e,e'p)^{11}\text{B}_{gs}$ reaction, indicating additional reaction mechanisms beyond the usually assumed quasi-free production.

A challenge in this field is to test the understanding of Quantum Chromodynamics in the non-perturbative regime, in particular the manifestations of Chiral Symmetry. Photon beams as well as high energy pion beams provide opportunities here for a rich experimental programme. Large acceptance detectors (CLAS at Jefferson Lab, Crystal Barrel at ELSA and HADES at GSI) will provide access to an extensive research programme on photon and dilepton spectroscopy which addresses the elementary properties of hadrons as well as their pos-

![Graph](image_url)  
Figure 7.4: The cross section for photoabsorption from a nucleon in $^{12}\text{C}$ compared to the free nucleon cross section.
sible modification within the nuclear medium. The electromagnetic structure of mesons and baryons can be studied by measuring their time-like formfactors which are important ingredients in any modelling of hadrons. Transition formfactors can be deduced from the shape of the dilepton invariant mass spectra from $\gamma e^+e^-$ or $\gamma\gamma e^+e^-$ Dalitz decays of neutral mesons. A precise knowledge of these formfactors is also important for a quantitative understanding of dilepton spectra from heavy ion and $\tau$-induced reactions. Measuring $e^+e^-$-decays of vector mesons in nuclei or compressed hadronic matter, formed in nucleus-nucleus collisions, will test the prediction for meson mass shifts with increasing baryon density, associated in some model calculations with the restoration of chiral symmetry. An enhancement of dilepton yields recently observed in relativistic and nonrelativistic heavy ion reactions may be first evidence for such medium modifications of hadrons.

7.4 Hadron Structure

7.4.1 Meson Spectroscopy

The past five years were characterised by an impressive step forward due to the efficient operation of the LEAR machine at CERN and to a co-ordinated use of two advanced wide angle spectrometers for neutral and charged particle detection (Crystal Barrel and Obelix), which started operation in 1990. More than $10^9$ events in $\bar{p}p$ annihilation were collected, about three orders of magnitude larger than previously available from Bubble Chambers. The analysis is far from being complete, but already very high statistics signals for new mesons have been found in $\bar{p}p$ annihilation in several channels.

One of these states, $f_0(1500)$ ($\Gamma_{tot} = 120\pm19$ MeV), has mass and width very much consistent with those anticipated for a glueball by lattice gauge (LGT) theories (Fig. 7.5). It is seen to decay in the channels $\pi\pi$, $4\pi$, $\eta\eta$, $\eta\eta'$ and $K\bar{K}$. The most likely interpretation is that this is the scalar glueball mixed with the $J^{PC} = 0^{++}$ $q\bar{q}$ nonet also expected in this region. Other possible members of this nonet, such as $a_0(1450)$ and $f_0(1370)$, have also been identified at LEAR.

![Figure 7.5: Glueball production observed by the Crystal Barrel in $\bar{p}p$ collisions at LEAR. Before operation of LEAR, the world total number of events in $\bar{p}p \rightarrow \pi\pi\pi$ was only a few hundred. Today a million events have been measured, revealing detailed structure in the Dalitz plot. The horizontal band marked X reveals the existence of a scalar meson mass 1500 MeV/c^2 with properties consistent with the lightest glueball, predicted by lattice gauge theory.](image)

The $f_0(1500)$ was previously observed with limited statistics (typically 100 decays or less) in central collisions at the $\Omega$- spectrometer at CERN, by the GAMS Collaboration in peripheral production with $\pi^-$ beams and in $J/\psi$ radiative decay (Mark III and Beijing). The decisive progress achieved at LEAR is mostly due to the enormous statistical samples (typically $10^5$ $f_0(1500)$ decays) made possible by the $4\pi$ acceptance of the detectors, together with substantial refinements in the analysis tools.

7.4.2 Glueballs

The mass region below 1500 MeV will probably be unraveled once the data from LEAR have been fully analysed. However, the definitive identification of $f_0(1500)$ as a glueball depends on the other $q\bar{q}$ scalars in particular the $s\bar{s}$ scalar which is still missing. All these states lie in the poorly known mass spectrum above 1600 MeV. Unfortunately, this region will not be accessible any longer at LEAR due to its recent closure.
Glueballs may be distinguished from $q\bar{q}$ mesons in central production. The WA102 collaboration at CERN has discovered that $q\bar{q}$ meson production appears to be suppressed in certain kinematic domains and that the glueball signals survive. The $f_0(1500)$ is seen clearly supporting the glueball interpretation; an extensive investigation is now required.

The first glueball excitation $(2^{++})$ is expected to lie between 2.0 and 2.4 GeV. An intriguing, relatively narrow ($\sim 40$ MeV), state, $f_2(2220)$ (also known as $\xi$), has been observed by Mark III in radiative $J/\psi$ decay and is now also seen at Beijing in several two-pseudoscalar decay modes, with relative rates compatible with flavour blindness. Poor statistics does not allow a determination of its quantum numbers (spin 2 or 4) nor an accurate determination of its decay branching ratios. If $J = 2$, this could be the first excited state of glue predicted by lattice gauge theories.

All these issues could be addressed with high statistics data (i) in central collisions, i.e. with the COMPASS experiment at CERN from 1999, and (ii) in radiative $J/\psi$ decay at a $\tau$-charm factory.

The other inspiration is that, if the $f_0(1500)$ has established the mass scale for excitation of the non-perturbative gluonic fields, it suggests that there should be new varieties of mesons, around 1.5 to 2 GeV, where the gluonic fields are excited in the presence of the quarks. These so called hybrid mesons may also now be emerging in experiments. One example is a state with exotic quantum numbers, $J^{PC} = 1^{-+}$ that are unattainable from the excitation of quark degrees of freedom alone. Recently the experiments E852 at Brookhaven and Crystal Barrel at LEAR have found for a $1^{-+}$ state near 1400 MeV/$c^2$ decaying into a $\eta\pi$-$p$ wave which would be the first unambiguous proof for the existence of a state with exotic quantum numbers.

Around 1900 MeV a new $2^{-+}$ state found by Crystal Barrel, $\eta_2(1875)$, has decay modes compatible with it being a hybrid state. Also in this interesting mass region, at 1.8 GeV, is an excitation of the pion, $\pi(1800)$, whose decay properties are as predicted for hybrid excitations; there is also data from Serpukhov indicating that this state has significant decay into the glueball candidate ($\pi(1500) \rightarrow \pi + f_0(1500)$).

The possibility that the excited gluonic modes are being “radiated” as a glueball could have interesting implications for the electro-production programme at the Jefferson Lab. Whereas mesons made from quarks may be produced at both the baryon and current (small $t$) vertices, a glueball can be produced dominantly at the baryonic vertex since it has no intrinsic coupling to photons. The study of the hybrid candidates will be made at the Jefferson Lab and also in a major programme in hadron spectroscopy with the COMPASS detector.

### 7.4.3 Form Factors

The study of nucleon form factors, which provide the most detailed information on the spatial distribution of quarks and currents in the nucleon, has entered a new era with the availability of high duty factor beams of polarised electrons. In particular this enables study of the neutron form factors, which have been notoriously difficult to measure. The programme includes $(e,e'n)$ coincidence experiments and $\overline{A}(e,e'n)$ experiments (where the nucleus $A$ contains a polarised neutron) with an order of magnitude improvement in precision. The first precise results using an intense beam of polarised electrons, a polarised target and a neutron polarimeter have been obtained at NAMI.

In the time-like region, the FENICE experiment at Frascati measured the $e^+e^- \rightarrow \bar{n}n$ cross section near threshold. The analysis has shown quite unexpected and interesting results: While PQCD expects that the ratio between neutron and proton magnetic form factors should be $\sim |q_n/q_p = \frac{1}{2}|$, the neutron magnetic form is found to be larger than the proton one. The data suggest that $|G_E^N| = |G_M^N| \simeq 0$ at threshold and that $|G_M^P|$ has a very steep rise. The differing $Q^2$ behaviours of the neutron and proton form factors near threshold hint at an interference with a narrow structure below threshold.

QCD implies that there is non-trivial mixing of D-states, quark-gluon and SU(6) repre-
presentations in the nucleon. These poorly known effects give characteristic behaviour to both elastic scattering and also $N^*$ resonance excitation. The use of polarised GeV energy electron beams and polarised targets in particular will be of special interest to disentangle the structure of the nucleon (transition) form factors in the resonance region (cf. $N^*$ programme at CEBAF).

Experiments on parity violation will provide important additional knowledge on questions such as the contribution of strange quarks to the spin of the nucleon. A possible strange component in the proton ground state would induce new terms in the electromagnetic current which violate parity conservation. The determination of the corresponding form factors is ongoing at BATES and will be carried out at MAMI and CEBAF (Jefferson Lab) during the next years. Finally, the determination of the $Q^2$ evolution of the spin response function of the nucleon, as well as of the Gerasimov Drell Hearn sum rule, will provide a link between the low energy sector and the asymptotic energy regime. An extensive research programme on the Gerasimov Drell Hearn sum rule, is planned at ELSA, GRAAL, MAMI, in Europe and at Jefferson Lab and LEGS (Brookhaven) in the United States.

7.4.4 Quark and Gluon Densities

In the regime of deep inelastic scattering, QCD is ideally suited to analyse quark and gluon dynamics in hadrons. The cross sections factorise into non-perturbative, or soft parts, and perturbatively calculable hard parts. Computational tools that have been developed over years enable accurate computation of the hard parts and to go to higher orders in perturbation theory. This is certainly one of the achievements in the last five years. This major progress is strikingly illustrated by the $Q^2$ evolution of the B"orken sum rule. This sum rule relates the first moment of the difference of polarised structure functions for proton and neutron measured in high-energy electron-proton, electron-deuteron and electron-$^3$He scattering. Within this framework the soft part has been determined and detailed knowledge has been obtained on the quark and gluon distribution in the nucleon.

The proton structure function $F_2$ has been accurately determined by NMC ($x > 10^{-2}$) and at HERA (down to $x \approx 10^{-4}$). The gluon density $G(x)$ has been determined at HERA down to $x \approx 10^{-4}$. The spin structure of the nucleon has been studied at CERN (SMC), SLAC and DESY (HERMES). Fig. 7.6 is a summary of all existing data.

![Figure 7.6: The polarised structure functions of the proton, of the deuteron and of the neutron measured at CERN, DESY and SLAC. The analysis of these data confirm the validity of QCD from the low energy region of $\beta$-decay to the high energy deep inelastic region. These results demonstrate that a significant fraction of the nucleon spin is either carried by gluons or by strange quarks from the sea. (Source: CERN, DESY, SLAC)](image)

The results corroborate the Bj"orken sum rule, when higher order QCD corrections are taken into account. This provides a beautiful confirmation that QCD accurately describes strong interactions over an energy range from $\beta$-decay to the highest collider energies. The surprise is that quarks carry only a small fraction of the nucleon spin. Yet, the quark model has been very successful in describing the phenomenology of strongly interacting particles. We know that
constituent quarks are composite objects made of a quark interacting with a sea of gluons and of virtual quark–antiquark pairs. Polarised electron and muon scattering experiments show that the role played by the sea is a significant effect. The possibility of a $s\bar{s}$ “vacuum polarisation” in the nucleon now needs to be determined with the best accuracy possible. An important issue is the size of the contribution of the “axial anomaly” and the closely related question of gluon polarisation. The various proposed theoretical ideas differ considerably in their predictions of the amount of spin carried by gluons. Several experiments have been proposed to measure the amount of gluon polarisation, at CERN (COMPASS), at HERA and at the new Relativistic Heavy Ion Collider (RHIC) being constructed at Brookhaven in the US. This future generation of polarised scattering experiments should resolve the enigma of the proton spin.

Finally, new information on the flavour structure of the nucleon has been obtained by the NMC collaboration. It appears that there are more anti-down than anti-up quarks in a proton. A possible explanation, only qualitative for the moment, could be the presence of pionic quark-antiquark correlations in the proton wavefunction.

In the years to come one hopes to refine the knowledge on the nucleon spin decomposition over spin and orbital angular momentum of quarks and gluons. Experiments such as in lepton production of charm or Deeply Virtual Compton Scattering, COMPASS (CERN) and HERMES (DESY), are expected to contribute significantly to our insight. This may confirm improved theoretical understanding of nucleon structure as obtained from lattice gauge calculations or may inspire new approaches towards understanding confinement.

At HERMES, the use of polarisation, as well as the detection of particles in semi-inclusive (in particular 1-particle inclusive) scattering processes, will allow the determination of nontrivial correlation functions. This requires particle identification in order to have flavour recognition and also good angular resolution in order to study azimuthal asymmetries which provide ways to study the dependence on the quark transverse momentum distribution. Furthermore, polarimetry in the final state is an important ingredient from which new information is expected. Such a study of non-leading effects in 1-particle inclusive lepton-hadron scattering will complement, or be complemented by, measurements in hadron-hadron scattering, especially Drell-Yan measurements (e.g. RHIC at Brookhaven) and fragmentation studies in $e^+e^-$ annihilation at LEP.

At HERA, the priority will be put on reaching the nominal luminosity (a few hundred pb$^{-1}$) and getting more accurate data. The study of the properties of the hadronic final state could be undertaken and shed some light on the origin of the rapid rise of the proton structure function $F_2$ at low $x$. More statistics on two jet events will lead to a more accurate determination of the gluon distribution $G(x)$ and its evolution. A more systematic study of diffractive events will lead to a better understanding of the nature and the structure of the Pomeron. The detection of the recoiling proton at the most forward angles may not allow to take full advantage of the improved luminosity.

### 7.4.5 Strangeness

The study of strangeness will be addressed with hadronic as well as with electromagnetic probes. In both cases selected spin observables will provide a way to reveal interesting small amplitudes through their interferences with the dominant ones. During the next decade, the proton beam of COSY (Jülich), the secondary kaon beam of DAΦNE (Frascati) as well as electron and photon beams of CEBAF (Newport News), GRAAL (Grenoble) and ELSA (Bonn) will allow the low energy sector of this field to be covered. At the beginning of next century, a new hadronic facility at Tsukuba in Japan (JHP) will make accessible its high energy sector.

In the 1960s a comprehensive study of kaon-nucleon scattering, as well as kaon production in pion-nucleon collisions, led to a fair determination of the corresponding partial wave amplitudes. On the contrary, the data set available in kaon photo- and electroproduction channels
is meagre and precludes a meaningful determination of the corresponding multipoles.

In the next five years, the combined analysis of the data obtained with the intense, monochromatic and polarised beams of real photons at CEBAF, GRAAL and ELSA will make possible such an amplitude decomposition in the resonance region \( \sqrt{s} - m \leq 1 \text{ GeV} \). Above the resonance region (up to \( E_{\gamma} \simeq 6 \text{ GeV} \)), Jefferson Lab will enter the regime where cross-sections are dominated by hard scattering on constituent quarks around 90° and large transverse momentum. The determination of the kaon electromagnetic form factor will be carried out at Jefferson Lab, up to \( Q^2 \simeq 4 \text{ GeV}^2 \).

Our knowledge of the free hyperon-nucleon (YN) interaction relies only on old bubble chamber data. The statistics are low and the range of the hyperons prevents access to low energy scatterings. It is remarkable that the only determination of the YN scattering lengths comes from the analysis of the energy spectrum of hypernuclei. To overcome this difficulty hyperons must be produced in nuclear reactions, in kinematics which enhance YN rescattering in the final state. For instance, the spectrum of the kaons emitted in the reaction \( pp \rightarrow K^+\Lambda p \) has been measured at SATURNE. Its high energy part, which corresponds to a very small relative energy between the emitted proton and kaon, exhibits an enhancement due to the strong YN interaction in \( S \) waves. A cusp, due to the strong coupling between the \( \Lambda N \) and \( \Sigma N \) channels, has been observed at the \( \Sigma \) production threshold. These measurements will be pursued at COSY with clever techniques pioneered at LEAR in the study of the \( \bar{p}p \rightarrow \bar{Y}Y \) \( (Y = \Lambda, \Sigma) \) reaction close to threshold. The study of spin correlations between two polarised colliding protons will disentangle YN rescattering in the \( 3S_1 \) and \( 1S_0 \) states. At Jefferson Lab a complete mapping of the cross-section of the reaction \( D(\gamma,K^+\Lambda)n \) will be achieved with the new large acceptance detector CLAS. The measurement of the polarisation of the emitted \( \Lambda \), as well as the use of polarised photons, will determine in details the nature of YN interaction.

Strangeness can also be hidden in hadronic matter. For instance the \( s\bar{s} \) component dominates the wave function of the \( \phi \) meson, which decays mainly into a pair of kaons. To a lesser extent, the wave function of the \( \eta \) and \( \eta' \) mesons contains a small \( s\bar{s} \) component. There are also speculations that the ground state of nucleons and nuclei may contain a sizeable strange component, which may be at the origin of evasions from the OZI selection rule as well as new parity violating effects. One of the major achievements is the large violations to the OZI rule observed at LEAR by the Obelix and Crystal Barrel Collaborations. Production of \( \phi \) following the annihilation of \( \bar{p} \) and \( n \) was particularly abundant in channels with a \( \pi \) or a \( \gamma \) in the final states, nearly two orders of magnitude larger than predicted by the simple OZI rule. Among the different explanations for such an effect, the one based on the presence of strange quark-antiquark pair \( (s\bar{s}) \) in the nucleon seems the most likely. At moderate momentum transfer, a possible \( s\bar{s} \) component may be knocked out by a virtual photon and eventually couple to the \( \phi \) meson. It can be revealed though interference with the dominant diffractive background as well as through amplitudes which do not conserve helicity.

7.5 New Physics Opportunities

7.5.1 Semi-inclusive Deep Inelastic Scattering

Nearly all existing data on quark distributions in hadrons have been obtained by inclusive scattering of high energy particles. In such reactions, one strikes quarks with considerable momentum and energy and reconstructs quark distributions from scattering data. This is possible because of a property of factorisation of the scattering amplitudes in quantum field theory. This property has allowed theory to find a firm basis for the partonic description and to go beyond the original model proposed by Feynman and Bjorken. The experimental observation amounts to an average over all the possible quark configurations in the nucleus. In addition to fundamental tests of QCD, the measurements of structure functions have lead to the discovery of the importance of gluons in the momentum and spin dis-
the correlations appear in the cross section via power-suppressed \((1/Q)\) terms.

A full exploitation of the possibilities of semi-inclusive processes requires polarised beams and targets in combination with sufficiently high energies in the range \(\sqrt{s} \simeq 10 - 30\) GeV. This energy regime is adapted to the correlation length for quark and gluon fields of the order of 0.3 fm and allows to cover the transition from the perturbative to the non-perturbative regime of QCD. It would be a qualitative leap towards precision experiments if luminosities of about \(10^{33}\) cm\(^{-2}\) s\(^{-1}\) could be reached in a collider geometry with both beams highly polarised. These are the design features of the electron-electron collider (ENC), proposed at GSI, a double ring system colliding electrons of 2.5 to 7.5 GeV with nucleons of nuclei of 10 to 30 GeV/u. This collider with full acceptance for the final hadronic state would be well suited for the study of semi-inclusive reactions.

### 7.5.2 Hard Exclusive Reactions

To understand how simple quark configurations are controlled by confining mechanisms, one needs a different type of data sensitive to the time evolution of a system of correlated quarks. This is the domain of exclusive reactions where scattered particles emitted in a specific channel are observed in coincidence.

Exclusive reactions are processes in which the final state is completely resolved. These reactions probe hadronic structure at very small distances \(\lambda\) by transferring to the target a large momentum transfer \(Q = 1/\lambda\). Hadrons behave as a collection of quasi-free objects, the partons, sharing each a fraction \(0 < x_i < 1\) of the infinite momentum and moving closely parallel to it. They are bound by the strong colour force, but their binding energy being small compared to their momentum, they behave almost freely. The parton model is for photon-hadron interactions what the impulse approximation is for nuclei. The major difference is that due to the existence of confinement, partons cannot be directly observed.

In hard exclusive reactions, the wave func-
tion of a composite state such as the proton can be written as a simple expansion of states with a fixed number of quarks and gluons. The valence component turns out to be the dominant one in hard exclusive reactions. The valence wave functions depend on the light-cone momentum fraction $x_i$, transverse momentum $p_T$ and helicities. They contain important information on quark confinement dynamics. The experimental strategy of ELFE physics is to sort out the hadron distribution amplitudes from various exclusive reactions, to learn about the dynamics of confinement. This is possible thanks to the fact that, within perturbative QCD, one derives a factorisation property of exclusive scattering amplitudes. The hard scattering amplitude is calculable perturbatively as an expansion in $\alpha_s(Q^2)$ free of large logarithmic corrections.

Exclusive reactions at high momentum transfer (form factors, real or virtual Compton scattering, photo- or electroproduction of pseudoscalar and vector mesons) will give access to the simplest partonic configurations of the hadrons. This requires higher luminosities, available only at Jefferson Lab in the near future. A significant increase of the energy beyond that available at Jefferson Lab is needed. However, accelerators designed for studying electroweak physics or QCD in inclusive reactions do not give us an access to exclusive scattering, because of the smallness of exclusive amplitudes at large transfers. The only possibility is to use a dedicated high intensity continuous beam electron accelerator to sort exclusive reactions at high momentum transfer. A new dedicated European facility such as ELFE will provide a unique window here.

7.5.3 The Nucleus as a Laboratory

Colour Transparency

colour transparency illustrates the power of hard exclusive reactions to isolate simple elementary quark configurations. Large $Q^2$ experiments select very simple quark configurations where connected quarks are close together, and form small size hadrons. These mini-hadrons are not stationary states but evolve in time to build up normal hadrons. Such colour singlet systems cannot emit or absorb soft gluons, which carry energy or momentum smaller than $Q$. This is because gluon radiation is a coherent process and there is thus destructive interference between gluon emission amplitudes by quarks with “opposite” colour. Even without knowing exactly how exchanges of soft gluons and other constituents create strong interactions, we know that these interactions must be turned off for small colour singlet objects.

Letting the mini-state evolve during its travel through different nuclei of various sizes allows an indirect but unique way to test how the squeezed mini-state goes back to its full size and complexity, i.e. how quarks inside the proton rearrange themselves spatially to “reconstruct” a normal size hadron. In this respect the observation of baryonic resonance production as well as detailed spin studies are mandatory.

The results on proton scattering on nuclei and $\rho$ meson lepto-production have to be confirmed. The study of the $A(e,e'p)$ reactions at SLAC does not show any significant effect. It is likely that the values of $Q^2$ are too low to observe colour transparency in the quasi free kinematics channel. An alternate way is to study reactions induced by electrons in few body systems. The kinematics should be chosen such that the interactions of the emerging hadron with a second nucleon are maximal. This maximum occurs when the produced hadron propagates on-shell. A clear signal for colour transparency would be the suppression of final state interactions when the momentum transfer increases. The study of colour transparency with hadronic probes has been proposed by measuring $J\psi$ production in $\bar{p}$ - nuclei collisions.

Existing high energy electron accelerators designed to study electroweak physics have intensities too low to study such exclusive reactions. Jefferson Lab provides an intense continuous beam of electrons, but its energy is too low. One needs a dedicated high energy and high intensity continuous beam electron facility such as ELFE.
Non-linear Low-x Effects

In the long term, the acceleration of nuclei in HERA may appear to be a powerful way to address two issues raised by the present data at low $x$: Unitary constraints on the rise of $F_2(x)$ or $G(x)$, and the nature of the pomeron. Up to now unitarity limits have not been reached in lepton-nucleon collisions. However, the lifetime of the hadronic content of the exchanged virtual photon is large ($\sim 1/x$) and exceeds the size of a nucleus (while its transverse extension, $\sim 1/Q$, is very small). It sees gluons, radiated by different nucleons in the nucleus, which may fuse, leading to non linear effects in the evolution equations at larger values of $x$ than in the free nucleon case. Speculations indicate that this should occur in nuclei in the range $x = 10^{-3}$ to $10^{-2}$ accessible at HERA. If the origin of large rapidity gap diffractive events were the exchange of many soft gluons, the viscosity of other nucleons will certainly modify significantly the free nucleon cross-section.

The acceleration of nuclei in HERA is a way to approach confinement in a regime where many partons are present in a small interaction volume. This is complementary to the study of exclusive reactions at large momentum transfer, which select the simplest partonic systems, but which require luminosities unreachable in the colliding mode.

7.6 How to proceed

The investigation of hadron and quark dynamics at accelerators is carried out with three types of probes.

1. Lepton probes of hadrons.

2. Hadron probes of hadrons.

3. Hadron production via $e^+e^-$ annihilation.

The advantages of leptons as a probe are well known. They involve electroweak processes that are to a good approximation single-step interactions. In lepton-hadron scattering the spatial resolution can be easily tuned. For momentum transfers of order 0.5 GeV one sees nucleons in nuclei, for transfers larger than 1 GeV one becomes sensitive to the quark constituents. To probe the scale of short distances, experiments require high momentum transfer and high energy. To explore correlations between quarks and gluons, one also needs polarisation and identification of the final states. High luminosity is an essential requirement for exclusive scattering.

Hadron beams allow one to study hadron dynamics and spectroscopy. For example, one can study hadron excitations and their decays. Observation of particles with specific quantum numbers serves as a filter that allows investigation of the composition of hadrons, e.g. strangeness, charm, glue. Another possible filter is to look for final states sensitive to specific interactions, e.g. lepton pairs ($e^+e^-$, $\mu^+\mu^-$) or photons.

Finally, it is possible to use $e^+e^-$ colliders to study properties of the hadrons that are produced with opposite quantum numbers in collinear pairs, for example strangeness ($e^+e^- \rightarrow K^+K^-$) or baryon number ($e^+e^- \rightarrow pp$). This is the case of the new $e^+e^-$ collider at the $\phi$ mass (DAΦNE) which will start operating in 1998 at Frascati, in Italy. A possible extension to 2 GeV and to a $\tau$ charm factory will be considered in the future. Other projects such as the RHIC spin programme in the United States,
Table 7.2: European hadron facilities operating in 2000 and beyond.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Projectile</th>
<th>Energy (GeV)</th>
<th>(\mathcal{L}) (cm(^{-2})s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAΦNE</td>
<td>(e^+e^- \to \phi \to K^+K^-)</td>
<td>0.016 (K)</td>
<td>(10^{23})</td>
</tr>
<tr>
<td>COSY</td>
<td>p</td>
<td>2.5</td>
<td>(10^9) p/s</td>
</tr>
<tr>
<td>CELSIUS</td>
<td>p</td>
<td>1.36</td>
<td>(2 \times 10^{32})</td>
</tr>
</tbody>
</table>

\(B\) factories in the United States and Japan will also yield important information on hadron and quark dynamics.

Some research areas are not covered by European facilities: thus, several European groups participate in collaborations in the United States, for example at Jefferson Lab and SLAC. Some areas are not yet covered anywhere in the world, such as a high intensity proton facilities in the energy range 30-50 GeV. To cover this area, Japan has proposed to build at KEK a 50 GeV high intensity (10 \(\mu\)A) proton accelerator dedicated to hadron probes. This project with its variety of secondary beams is likely to become a world class hadron facility.

**7.7 Recommendations**

From a global perspective, and on grounds of physics opportunity, complementarity between facilities and timeliness, a natural focus for Europe is the probe of hadrons via electron beams.

NuPECC’s original endorsement of a European electron facility (ELFE 1991) has led to intensive studies of the physics and its experimental realisation. These studies have revealed that such a facility can bring unique insights into non-perturbative QCD via exclusive and semi-inclusive scattering. These studies confirm and reinforce our recommendation that a high intensity and high duty cycle electron laboratory at \(\sqrt{s} = 7\) GeV or above be constructed in Europe.

We note also that various national laboratories in Europe are considering facilities that, if realised, could have significant interest for the hadron and quark dynamics community. These include a fast cycling proton synchrotron at GSI and, in the shorter term, a \(\tau\)/charm factory at Frascati. We encourage these national institutions to pursue these aims with the hope that they may be realised as international facilities.

As a general strategy, we recommend R&D on high intensity, high duty cycle electron acceleration and electron cooling techniques at high energy.
8. Nuclear and Particle Astrophysics

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8.1 Recent Highlights

Astronomical observations of the universe and its contents, such as galaxies, stars, the interstellar
and intergalactic medium, rely traditionally on a variety of wavelength bands of the electromagnetic
spectrum (e.g., radio, microwave, IR, optical, UV, X-rays). In recent years, however, also observations
which detect particles, like neutrinos, high energy cosmic rays, as well as gamma-rays, have gained importance and added
new insight. Abundances of elements/nuclei can often be determined from radio lines of interstellar
matter, quasar absorption lines, stellar spectra, spectra of explosive events like novae and supernovae, the light from entire galaxies, X-ray lines of hot interstellar and intergalactic gas and gamma-ray lines of decaying unstable (but often long-lived) radioactive nuclei. The explanation of such findings requires the knowledge and role of nuclear and particle physics in a large variety of astrophysical events.

Past and ongoing research have led to impressive progress, resulting - with regard to ob-
servations - in highlights like the perfect blackbody spectrum of the cosmic microwave background, detected by the COBE satellite; the very small but existing anisotropies in the spectrum, probably related to high energy physics aspects of the early universe; the first detection of solar neutrinos from the dominant pp-
cycle reactions by GALLEX and SAGE; neutrino measurements from Supernova 1987A by
the KAMIOKANDE, IMB and BAKSAN detectors, supporting the core collapse picture; many
abundance determinations in the ejecta, calling for multidimensional effects; the detection of X-
spectra by ROSAT and ASCA, revealing the composition of interstellar and intergalactic gas;
the detection of gamma-rays from supernova remnants by the Compton Gamma Ray Ob-
servatory (CGRO), stemming from $^{56,57}$Co and $^{44}$Ti decay; the all sky mapping of $^{26}$Al; the first
detection of nuclear deexcitation lines of $^{12}$C and $^{16}$O (due to nuclear interactions); the detection
of high Si, S, and Ar abundances in some novae, indicating the existence of ONeMg white
dwarfs; the detection of type Ia supernovae at high redshifts and their use as cosmological dis-
tance indicators; the detection of gamma-ray bursts in the keV to GeV range by CGRO (most
recently also the detection of X-ray and optical counterparts); cosmic ray experiments with improved abundance measurements (ULYSSES); the detection of ultra-high energy cosmic rays in the range $10^{20}$ eV (FLY’S EYE, AGASA, HAV-
ERAH PARK, YAKUTSK) and rapidly varying gamma rays in the TeV range (CAT, HEGRA,
WHIPPLE) with clear source indications; high precision measurements of abundances in low
metallicity stars including heavy r-process elements (HUBBLE); abundance determinations
via quasar absorption lines at high redshifts, i.e. in very young galaxies; and the birth of “iso-
topic” astronomy by abundance determinations in dust grains from stellar ejecta, imbedded in
meteoritic material.

Laboratory experiments in nuclear physics permitted a high precision determination of the
neutron half-life with ultra-cold neutrons, affect-
ing big bang nucleosynthesis; for the first time cross section measurements at stellar burning energies [the \(^{3}\text{He}\left(^{3}\text{He},2\text{p}\right)^{4}\text{He}\) reaction] in a pilot underground experiment shielded from the cosmic ray background (LUNA); the measurement of screening effects in nuclear reactions due to electrons present in the target and/or projectile; the determination of the E1 contribution to the very important \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) reaction; prompt measurements of microbarn neutron capture cross sections for light nuclei; the first capture cross section measurement of a radioactive nucleus with radioactive beams in inverse kinematics (\(^{13}\text{N}(p,\gamma)^{14}\text{O}\) at Louvain-la-Neuve); radioactive beam measurements at Louvain and elsewhere, aided by new detector arrays (developed for nuclear structure work) and recoil mass separators; the detection of bound state beta-decay of fully ionized nuclei like \(^{187}\text{Re}\) in the GSI storage ring; the discovery of doubly-magic nuclei like \(^{78}\text{Ni},^{100}\text{Sn}\), and single particle orbitals in \(^{132}\text{Sn}\), "superheavy" Z=112 and nuclei far from stability in the r- and rp-process path at CERN/ISOLDE, SPIRAL/GANIL, GSI, and NSCL/MSU; the investigation of the Coulomb dissociation technique as a possible alternative for the measurement of capture cross sections at GANIL, GSI, MSU and RIKEN; the detection of neutrino nucleus cross sections at KARMEN and LSND; relativistic heavy ion collisions which probed super-nuclear densities, important for the neutron star equation of state and the quark-hadron phase transition in the early universe; to name a few.

The advances in computing facilities and developed numerical methods permitted two and three-dimensional modelling of astrophysical events with an increased amount of microphysics included. Nuclear theory developed Monte Carlo shell model techniques for nuclei beyond the fp-shell and at finite temperatures, attacked important aspects of nuclear structure far from stability, including the effect of shell quenching towards drip-lines; determined properties of neutron-rich matter at subnuclear densities, important for the equation of state in supernova collapse and neutron star crusts; and permitted to predict neutrino capture cross sections on nuclei. Particle physics research led to the result that baryon number conservation is violated by non-perturbative effects in electroweak interactions, an effect which is of importance for the matter-antimatter asymmetry of the early universe and continued to explore properties of matter near the Grand Unification (GUT) regime, related to spontaneous symmetry breaking, topological defects and inflation, possibly responsible for anisotropies in the early universe and later structure formation.

Despite this impressive progress at adjacent fronts, there remain major puzzles which challenge the basis of astrophysics, e.g. the baryonic and total density of the universe, solar neutrinos, burning phases in stellar evolution and their resulting composition, the dynamics of supernovae, the nucleosynthesis products of explosive events, the supra-nuclear equation of state of nuclear matter in neutron stars, the origin of gamma-ray bursts and the source and composition of cosmic rays. The solution of these puzzles requires advances in terms of observations of astrophysical objects and in terms of laboratory studies of the physics involved. Both have to be complemented by theoretical modelling. In section 2 we present the major subfields of astrophysics which require nuclear and particle physics input. In section 3 we discuss ways how to proceed in determining this input, ranging from novel laboratory approaches to the quest of improvements in theory. In section 4 we summarise the relevance of these projects for this lively and exciting field of research and the need for future support by NuPECC and other organisations.

8.2 Astrophysical Sites

8.2.1 The early universe

The linear recession of galaxies, the cosmic microwave background (CMB) and the cosmic abundances of the light nuclides \(^{1}\text{H},^{2}\text{H},^{3}\text{He},^{4}\text{He},^{7}\text{Li}\) are the main observations supporting the idea that the present universe emerged from a hot and dense state by adiabatic expansion. Physicists are eager to unravel all the "relics" left over from these early epochs [1]. Big Bang Nucleosynthesis (BBN), occurring
at $T \approx 0.1$ MeV is presently the earliest epoch with such observable "relics" from a well understood process. When assuming that all microphysics is understood, the final BBN abundances of the light elements are determined by only one parameter, the entropy, expressible in terms of the baryon to photon ratio $\eta = n_B/n_\gamma$. Uncertainties, affecting especially the primordial $^4$He abundance, were related to $N_\nu$, the number of neutrino species and $\tau_n$, the neutron lifetime. However, in the late 1980's measurements of the properties of the $Z^0$ boson with the large electron-positron collider (LEP) at CERN led to $N_\nu=3$, and the neutron lifetime is now also known with sufficient accuracy due to experiments with trapped ultracold neutrons: $\tau_n = 887 \pm 2$ s. The cross sections of the relevant thermonuclear reactions linking nuclei from $^1$H to $^7$Li have been measured at the appropriate energies to an accuracy better than 10%. The major uncertainties are related to the determination of the primordial abundance of $^2$H, $^3,^4$He and $^7$Li with astronomical means. The abundances of the light elements constrain $\eta$ to $2.5 \times 10^{-10}$, and $\Omega_b h^2$ to 0.01-0.025, where $\Omega_b$ is the baryon fraction of the critical density of the universe and $h$ the Hubble expansion parameter in units of 100 km/s/Mpc ($H_o = 50-80$ km/s/Mpc) [2]. Many variants of the BBN model have been investigated to test the robustness of its nucleosynthetic predictions to "exotic" physics. The most extensively studied case concerns the possibility of an inhomogeneous early Universe, due to a first order QCD phase transition taking place at $T \sim 200$ MeV. Comparison of light element primordial abundances to the results of recent models of inhomogeneous nucleosynthesis shows, however, the need for baryon densities very similar to the ones resulting from the standard BBN.

Two dark matter problems arise from the above standard BBN constraints: (1) Baryons observed in form of starlight amount to $0.002 < \Omega_{\text{baryon}} h < 0.006$, i.e. there must be baryonic dark matter, (2) galaxies are constrained to $\Omega = 0.05 \pm 0.03$, clusters of galaxies indicate $\Omega > 0.15$, and large scale flows of galaxies in the universe $\Omega > 0.3$. Thus, most of the matter in the Universe has to be non-baryonic. Popular candidates are massive neutrinos and axions. The solution of the dark matter problem will require joint forces from astronomy and particle physics, investigating neutrino oscillations, accelerator searches for super-symmetry or direct dark matter searches (see also the working group on neutrino physics and fundamental interactions) [3]. Early epochs bear other open questions. The standard model of particle physics predicts the electroweak phase transition at a temperature $T_c \sim 200$ GeV and for $T > T_c$ baryon number violating processes (sphaleron transitions) are unsuppressed. The early universe might have left relics of this phase transition in the form of the observed baryon asymmetry, if the electroweak phase transition is of first order. Accelerator searches for the Higgs particle which induces this phase transition and better observational limits on the antimatter content of the universe will be very valuable to improve our understanding of the universal baryon asymmetry.

The present cosmic microwave background (CMB) radiation follows a perfect blackbody spectrum of $(2.727 \pm 0.01)K$ [4]. It decoupled from matter at about 3000 K ($\sim 0.3$ eV) when nuclei and electrons combined to neutral atoms. The COBE satellite found also that the CMB is extremely isotropic with $l > 1$ multipole amplitudes less than $10^{-4}$. The present matter distribution with anisotropies on scales up to about 50 Mpc must have grown out of small initial fluctuations by gravitational instabilities which caused structure and galaxy formation and should be visible as small fluctuations in the CMB. Two classes of models can predict such a spectrum of primordial fluctuations: (1) quantum fluctuations which expand to super horizon scales during a period of inflationary expansion and (2) a phase transition at a temperature of about $10^{16}$ GeV leading to topological defects. The CMB anisotropies may thus provide information about the physics at extremely high energy scales ($10^{14}-10^{16}$ GeV). A further understanding within a few years is expected by improved CMB observations (PLANCK, MAP), as both models lead to different CMB patterns in a multipole expansion.
8.2.2 Stellar evolution

Stellar evolution depends on nuclear, plasma and atomic physics and aspects related to theoretical modelling and hydrodynamics [5]. Investigations on important nuclear reactions in astrophysics were pioneered by Fowler and collaborators, with many open questions left until present [6]. A few are (a) pp-chain reactions in H-burning, which affect sub-solar and solar type stars and are directly connected to the solar neutrino emission, e.g. $^3\text{He}(\alpha, \gamma)^7\text{Be}$, $^7\text{Be}(p, \gamma)^8\text{B}$, $^7\text{Li}(p, \alpha)^4\text{He}$, CNO-cycle reactions like $^{14}\text{N}(p, \gamma)^{15}\text{O}$ and $^{17,18}\text{O}(p, \alpha)^{14,15}\text{N}$, which directly relate to the surface abundances in intermediate mass stars, NeNa-cycle reactions in intermediate and massive stars, (b) the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction in He-burning, and (c) fusion reactions of late burning stages, e.g. $^{12}\text{C} + ^{12}\text{C}$, which are not well known at low energies.

Massive stars, with initial masses beyond roughly 8 M$_\odot$, form an Fe-core after completing all nuclear burning stages. Its size is strongly dependent on the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate in He-burning, the treatment of convection, and the electron captures on nuclei in O- and Si-burning. The evolution after the onset of C-burning takes only several hundred to a 1000 years, due to efficient energy loss via neutrinos, rather than radiation. Low and intermediate mass stars lose mass by efficient stellar winds which leads to remaining stable C/O-cores below the Chandrasekhar limit after H- and He-burning. At high densities/low temperatures Fermions form a degenerate gas and the pressure depends only on the stellar density. In the nonrelativistic limit of Fermi energies the pressure is proportional to $\rho^{5/3}$, in the relativistic limit towards higher densities the pressure scales as $\rho^{1/3}$. Powers less or equal to 4/3 cannot support a stable object, which is the reason for the Chandrasekhar mass limit of white dwarfs (degenerate electrons) and the maximum neutron star mass (degenerate nucleons), where the uncertainties due to nuclear interactions play a role as well. Their formation will be discussed in section 2.3.

Based on stellar evolution models the energy generation in the Sun is provided to 98% by the nuclear fusion reactions of the pp-chains, while the CNO-cycle contributes 2%. Both hydrogen burning mechanisms are accompanied by the emission of neutrinos [7], which can provide immediate information on the details of the composition and the physical conditions at the solar centre. The detection of solar neutrinos is, therefore, a unique tool for the investigation of basic properties of the Sun, a typical star in the phase of core H-burning. Such information is complemented by helioseismology which can, due to the properties of the oscillation modes, deduce the radial dependence of composition as well as physical conditions. Discrepancies with model predictions give rise to the solar neutrino problem.

![Figure 8.1: The neutrino spectrum of weak interactions in the pp-cycle, $^1\text{H}(p, e^+\nu)^2\text{H}$, $^1\text{H}(e^-\bar{p}, \nu)^2\text{H}$, $^7\text{Be}(e^-, \nu)^7\text{Li}$, $^8\text{B}(e^+\nu)^8\text{Be}$ predicted by standard solar models [7]](image)

The existing four solar neutrino experiments have different neutrino energy thresholds: (1) the HOMESTAKE gold-mine, using the inverse $\beta$-decay reaction $^{37}\text{Cl}(\nu_e, e^-)^{37}\text{Ar}$ with a threshold energy of 814 keV, (2) the European GALLEX-experiment, based on the reaction $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$ with a uniquely low detection threshold of 233 keV, and (3) the Soviet-American Gallium Experiment SAGE which uses the same detection reaction as GALLEX but a different chemical composition of the Ga target; (4) finally, there are the Japanese experiments KAMIOKANDE and SU-
PERKAMIOKANDE, which are based on the detection of \( \nu-e \) scattering via Cerenkov light in large volume underground water tanks with an energy threshold of 7.5 MeV due to the radioactive background. The Kamiokande experiments are only sensitive to the \(^8\)B-neutrinos, but have additional direction information and can observe day/night effects. They see about 50% of the expected neutrino flux. The Homestake results, which should be dominated to 80% by the \(^8\)B neutrinos and to 20% by the \(^7\)Be and CNO neutrinos, show only 30% of the expected neutrino flux. GALLEX and SAGE, the only experiments detecting the high flux of pp-neutrinos, see about 50% of the expected total flux. Given these significantly suppressed neutrino rates, the standard model - being supported by helioseismology - leaves not much room for conventional solutions. Numerous studies indicate that neutrino oscillations appear to be the most likely explanation for the solar neutrino problem. This could be vacuum neutrino oscillations in space or the Mikheyev, Smirnov, Wolfenstein effect (MSW), inverting the neutrino mass hierarchy in (solar) matter. This would be a spectacular first indication for "new physics" beyond the standard model of electroweak interaction. For an unambiguous proof of these possible solutions and/or potential conclusions about neutrino properties, the input parameters, like nuclear reaction rates at solar energies and the solar neutrino energy spectrum, must be placed on a substantially improved basis. This can be achieved by ultra-low energy cross section measurements and a series of second-generation solar neutrino experiments.

He-burning can provide neutrinos in a stellar environment, produced e.g. by the sources
\[ ^{13}\text{C}(\alpha, n)^{16}\text{O} \text{ or } ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \]. The sequence
\[ ^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+\nu)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}(\alpha, n) \] produces \(^{22}\)Ne, with \(^{14}\)N being the main product of the CNO-cycle in the preceding H-burning. \(^{13}\)C can only be existent in sufficient amounts in He-burning environments, when some mixed in hydrogen acts on the abundant \(^{12}\)C nucleus via
\[ ^{12}\text{C}(p, \gamma)^{13}\text{N}(\beta^+)^{13}\text{C} \]. Both neutron sources lead to the \textbf{s-process}, being characterised by neutron captures which are slow in comparison to beta-decay rates and produce about one half of the observed abundances of the nuclides above \( A \sim 60 \). It is recognised to occur in at least two different astrophysical sites, the weak component accounting for most of the s-nuclei below the Kr-Rb-Sr abundance peak, and the main component accounting for heavier nuclei up to Pb. A third site (strong component) might be required to account for about 50% of the double magic nucleus \(^{208}\)Pb [8]. The main s-process component is due to the thermally-pulsing phase of shell He- and H-burning in low mass stars (\( M \leq 3\ \text{M}_\odot \)) and primarily driven by \(^{13}\text{C}(\alpha, n)^{16}\text{O} \) rather than \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \). Its composition can condensate into dust when expelled in form of stellar winds. Such dust grains are actually found in the form of incorporated \textbf{pre-solar grain inclusions} in solar system meteorites which show the expected isotopic anomalies [9]. Recent research indicates that \(^{13}\text{C}(\alpha, n)^{16}\text{O} \) burns in the interpulse phases at lower temperatures, i.e. lower neutron energies (\( \sim 8 \text{ keV} \)), where cross sections are often badly known. Core He-burning with the \(^{22}\)Ne source contributes to the weak s-component which is a complex combination of core He- and shell C-, and Ne-burning in massive stars. The latter two also involve neutron captures on a number of unstable nuclei, traditionally ascribed to the rapid neutron capture process (r-process).

Over the past 10 years impressive improvements have been achieved in the nuclear input data, mainly the stellar neutron capture cross sections for stable nuclei above Fe [8], while for light and intermediate mass nuclei, including C, O, Ne, Mg, Si, Ar, Ca, and Ti isotopes, which play a role as neutron poisons and in the composition of wind ejecta and dust grains, mostly old cross sections are available with generally large uncertainties. Experimental cross sections are also required for long-lived unstable nuclides involved in branchings due to comparable beta-decay and neutron capture rates [8]. Improved measurements of the small cross sections at neutron shell closures are necessary for a better description of the s-process and for discriminating among different stellar environments. Among the most important and difficult examples is the branching occurring at \(^{85}\)Kr, which involves Kr, the Rb and Sr isotopes. Decay properties of
fully ionized atoms, as occurring in stellar environments, differ from atomic decays and can be investigated at radioactive ion beam facilities. Important for the study of the weak s-process neutron source is the direct measurement of low energy resonances in $^{18}$O($\alpha,\gamma$)$^{22}$Ne and $^{22}$Ne($\alpha,n$)$^{25}$Mg.

### 8.2.3 Type II supernovae

The Fe-core, emerging after Si-burning in massive stars, undergoes a core collapse to neutron star densities. This leads either to type II supernovae (which display hydrogen lines in their spectra from the outer unburned envelope) and/or to black hole formation, if the core collapse produces an object beyond the neutron star mass limit. The discovery of 24 neutrinos with the KAMIOKANDE II, IMB, and BAKSAN underground laboratories for supernova SN 1987A confirmed this theoretical picture. These neutrinos, originating from the extremely dense and hot supernova core, could be utilised to derive constraints on neutrino properties, particle physics models, and nuclear physics [10]. Aspects which strongly enter the outcome are the (nuclear) equation of state and neutrino interactions with matter (nucleons, nuclei, electrons), together with the treatment of the hydrodynamics of the explosion, affecting strongly the mass cut between the central neutron star and the supernova ejecta. The observationally indicated mixing of radioactive elements must be interpreted as very strong indication of turbulent processes. Possibly such multidimensional processes can be of importance for the explosion mechanism itself [11]. Unfortunately, the few SN 1987A neutrino events did neither enable us to constrain the total energy release of the forming neutron star accurately, nor did they provide sufficiently detailed temporal and spectral resolution for a full understanding of the explosion of the star. Our hope in this respect rests on a future Galactic supernova to be detected by the next generation of neutrino experiments, e.g. SUPERKAMIOKANDE and SNO. They should be a probe of the physical events preceding the disruption of the star and contain a wealth of information about particle and nuclear physics at supernova conditions.

![Figure 8.2: A 2D simulation of a type II supernovae explosion](sn87a.png) The matter is heated by neutrinos from the hot proto-neutron star. Entropies are given in units of $k_B$/nucleon.

The explosive processing and nucleosynthesis in the ejecta gives rise to a large fraction of the present day element abundances. Explosive nucleosynthesis calculations require the knowledge of nuclear reaction rates at high temperatures, to a large extent for unstable nuclei, based on theoretical or experimental efforts. The comparison with abundances from specific supernova observations can probe the correctness of the stellar evolution treatment and the $^{12}$C($\alpha,\gamma$)$^{16}$O rate. SN 1987A showed reasonable agreement with C, O, Si, Cl, and Ar abundance observations. Supernova remnants make it possible to compare with the observational results from optical, UV, and X-ray observations. The delay time between collapse and explosion via neutrino heating determines the amount of accreted matter onto the proto-neutron star. Combined observations of the ejected $^{56}$Ni, as deduced from the $^{56}$Co powered supernova light curve observations, the $^{57}$Co/$^{56}$Co ratio from gamma-ray observations (possible in SN 1987A)
and the amount of $^{44}\text{Ti}$ (possible in Cas A) would give unique information on the position of the mass cut, the energy of the shock wave and the neutron/proton ratio in the innermost ejecta [12].

The very innermost layers of the ejecta, driven off the surface of the nascent, cooling neutron star and heated by a strong neutrino flux, might also include r-process nucleosynthesis, based on the built-up of heavy elements up to Th and U via rapid neutron captures. Provided that r-process conditions can be obtained [13], neutron densities and temperatures well in excess of $n_{n}>10^{28}\text{cm}^{-3}$ and $T>10^{9}\text{K}$ result, which cause reaction timescales as short as $\approx 10^{-4}\text{s}$, while the beta-decay half-lives of the involved nuclei are longer, roughly of the order of $10^{-1}$ to a few $10^{-3}\text{s}$. This approaches an $(n, \gamma)\rightarrow(\gamma, n)$ equilibrium and a capture path on contour lines of constant neutron separation energy in the nuclear chart. Only a few nuclei along the magic neutron numbers 50 and 82 are known in the regime of neutron separation energies between 2 and 4 MeV. A full understanding requires a highly increased amount of data and nuclear structure knowledge far from stability, i.e. masses, half-lives, possibly neutrino interaction cross sections and level densities and giant resonance properties to predict gamma widths [14] for the reaction rate calculations. The question whether shell closures are quenched for nuclei far from stability is here highly relevant and enters in an important way in the abundance features. Astrophysical uncertainties include the major question about the obtained entropies and n/p ratios in this matter and whether this material is finally ejected or hindered by fall back, due to reverse shocks in the ejected envelope.

### 8.2.4 Explosions in binary systems

Many events involving stellar binary systems are characterised by the revival of dormant, degenerate objects via mass overflow from the binary companion or binary mergers via gravitational radiation energy loss. Degenerate conditions prevent controlled burning and causes a thermonuclear runaway because a temperature increase does not lead to a pressure increase. Low accretion rates lead to a pile-up of unburned hydrogen, causing the ignition via pp-chains with pycnonuclear reaction enhancements (screening) when a critical mass layer is attained. This triggers nova events on white dwarfs and X-ray bursts on neutron stars. The nuclear energy source is explosive hydrogen burning, ranging from hot CNO-cycles to long sequences of proton captures and beta-decays (the rp-process [15]).

The main energy source in novae is the hot CNO-cycle, characterized by proton-induced reactions on radioactive nuclei like $^{13}\text{N}(p, \gamma)^{14}\text{O}$, $^{17}\text{F}(p, \gamma)^{18}\text{Ne}$, $^{18}\text{F}(p, \alpha)^{15}\text{O}$, and possibly $^{18}\text{F}(p, \gamma)^{19}\text{Ne}$. Present reaction rate information seems to indicate that the gap between the hot CNO-cycle and nuclei beyond Ne can only be overcome by alpha-capture reactions for temperatures above $4 \times 10^{8}\text{K}$, unlikely to be attained in novae. The observed high Si, S, and Ar abundances in some novae ask for a class of white dwarfs which was formed after core C-burning, containing O, Ne, and Mg. This permits nucleosynthesis up to $A\sim40$ (including $^{26}\text{Al}$) due to proton capture reaction sequences on the initial high Ne and Mg abundances. To understand and interpret these observations, detailed measurements of capture reactions on radioactive and stable isotopes in the Ne-Ca range are required.

The nucleosynthesis and energy generation in X-ray bursts and black hole accretion disks is dominated by combined H- and He-burning at extreme temperatures and densities [15]. The key nuclear properties for the energy generation and abundance predictions are break-out reactions from the hot CNO, e.g. $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}$ and proton captures on even-Z $T_{z}$=–1/2 nuclei like $^{23}\text{Mg}$, $^{27}\text{Si}$, $^{31}\text{S}$, $^{35}\text{Ar}$, and $^{39}\text{Ca}$ in competition with beta-decays and the connecting $(\alpha, p)$-reactions. Heavier and more proton-rich nuclei are only populated for conditions when a $(p, \gamma)\rightarrow(\gamma, p)$-equilibrium is approached, requiring essentially beta-decay half-lives and nuclear masses like in the r-process. Beyond Se, the details of the proton drip-line are not that well known yet, but can influence the endpoint of the rp-process. The even-even $N=Z$ nuclei between $A=68$ and 100 play a dominant role. First
calculations which include 2p-captures (coming to a \((p, \gamma)-(\gamma, p)\)-equilibrium with intermediate p-unstable nuclei) indicate that it seems possible to produce nuclei with \(A=90-100\) in X-ray bursts, including some hard to explain p-process nuclei.

Accretion rates above a critical limit cause stable H-burning or only weak flashes. Supersoft X-ray sources, observed by ROSAT, have been identified as white dwarfs with such accretion rates, subsequently experiencing He-accretion above the critical value for stable He-burning and producing a growing C/O white dwarf, which exceeds the Chandrasekhar mass and ignites carbon fusion degenerately with screening enhancements. A burning front propagates through the whole star, causing complete disruption without a remnant. Such objects are candidates for type I(a) supernovae, which observationally do not exhibit hydrogen lines in their spectra due to the absence of extended H-envelopes. Possible alternatives correspond to the ignition of a freshly accreted helium layer (He-detonations) and/or the merging of two white dwarfs in a binary system. In all of these cases a complete disruption of a white dwarf occurs with a large amount of \(^{56}\text{Ni}\) formation [16]. The propagation of the burning front occurs initially via heat conduction in the degenerate electron gas (requiring a spatial resolution in hydrodynamic calculations of the order \(10^{-4}-10^{-5}\) cm). Convective instabilities, leading to burning front propagation via convection, cause a detonation if they accelerate to supersonic speed. This behaviour is generally understood, but cannot be numerically resolved, yet. Observations favour the Chandrasekhar mass models and/or white dwarf mergers which follow this burning pattern. Type Ia supernovae are the main producers of Fe-peak elements in the Galaxy. Electron captures on the incinerated material and the neutron-excess due to the He-burning product \(^{22}\text{Ne}\), originating from the prior CNO metallicity, lead to the production of neutron-rich Fe-group nuclei which constrain critically the burning front propagation.

Another outcome of binary system evolution is a pair of neutron stars. The famous binary pulsar discovered by Hulse and Taylor is expected to lead to a merged system in about \(10^{8}\) y. From a purely statistical point of view the number of gamma-ray bursts observed with the Compton Gamma Ray Observatory (CGRO) [17] agrees with the expected number of neutron star mergers in the cosmos, and the isotropic behaviour agrees with homogeneously distributed roughly standard candles out to redshifts of \(z\approx 1\). It has to be verified whether such events can really reproduce the gamma-ray burst observations. A merger of two neutron stars may also lead to the ejection of neutron-rich material as an alternative site for the production of r-process elements [13]. A hydrodynamical calculation coupled with r-process calculations has still to be undertaken.

### 8.2.5 High energy astrophysics

Adding the products of big bang nucleosynthesis and the ejecta of all stellar sources in their right proportions and on the relevant timescales causes the galactic evolution of the elements. Crucial quantities are the predicted ejecta of the individual objects (stellar winds, type II supernovae, novae, possibly X-ray bursts, type Ia supernovae, neutron star mergers, etc.) and the statistical occurrence of the individual contributors [18]. Radioelements with half-lives ranging from roughly 100 days to the age of the Galaxy, like \(^{23}\text{Na}, \, ^{26}\text{Al}, \, ^{44}\text{Ti}, \, ^{56,57}\text{Co}, \, ^{182}\text{Hf}, \, ^{129}\text{I}, \, ^{223}\text{Th}, \, ^{235,238}\text{U}, \, ^{244}\text{Pu}\), being found in expanding explosion remnants, the interstellar medium or interstellar grains and meteorites, can provide information on the composition in individual events, the integral over galactic evolution or late additions to the forming solar system.

**Gamma-ray line astronomy** became a privileged tool for the study of stellar nucleosynthesis in the past ten years. The proximity of SN1987A and the launch of NASA's CGRO with the most powerful instruments ever operative played a major role in this rapid progress [19]. Among these, the COMPTEL telescope provides for the first time extensive possibilities for spatially resolved gamma-ray spectroscopy at MeV energies. This allowed to confront supernova models with observations (\(^{56}\text{Co}\) and
\( ^{57}\text{Co} \) in SN1987A, \( ^{56}\text{Co} \) in SN1991T and \( ^{44}\text{Ti} \) in CasA) and to locate the sites of large scale nucleosynthetic activity in the Galaxy through the profile of the \( ^{26}\text{Al} \) emission. Hidden supernovae in dense regions may be uncovered through their \( ^{44}\text{Ti} \) radioactivity in the 1.157 MeV line, thus constraining the Galactic supernova rate. The increased sensitivity of ESA’s INTEGRAL (to be launched in 2001) will allow to explore those issues further and tackle several other related topics: \( ^{22}\text{Na} \) from galactic novae, a chance close-by explosion (as with SN1987A) would make \( ^{56}\text{Co} \) and \( ^{57}\text{Co} \) observable, the detection of diffuse \( ^{60}\text{Fe} \) γ-ray lines at 1.2 and 1.3 MeV is expected from type II supernova models predicting a yield between 0.25-0.35 of the corresponding \( ^{26}\text{Al} \) yield.

![CGRO/COMPTEL 1.8 MeV All-Sky Map](image)

Figure 8.3: Intensities of the 1.8 MeV gamma transition following \( ^{26}\text{Al} \) decay in galactic co-ordinates, ranging from \( 10^{-7} \) (black) to \( 1.6 \times 10^{-3} \) photons cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) (bright yellow).

Gamma-ray observations by satellite experiments provide also unique opportunities to trace accelerated nuclei. Low-energy (\( \lesssim 100 \) MeV/nucleon) accelerated particles, interacting (scattering) with ambient matter, produce excited nuclei. Gamma-ray lines from energetic nuclei can be distinguished from those of ambient nuclei because they are Doppler broadened and can even contain line splitting features due to non-isotropic emission in the rest frame of the nucleus. Until recently, gamma-ray lines from accelerated particle interactions had been observed only from solar flares, e.g. \( ^{12}\text{C} \) (4.44 MeV), \( ^{16}\text{O} \) (6.13 MeV), \( ^{20}\text{Ne} \), \( ^{24}\text{Mg} \), \( ^{28}\text{Si} \) and \( ^{56}\text{Fe} \) in the 1–2 MeV range. COMPTEL has now detected emission in the 3–7 MeV range from the Orion complex, which can be identified as de-excitation of \( ^{12}\text{C} \) and \( ^{16}\text{O} \) at 4.44 and 6.13 MeV. This surprise indicates that a large flux of low-energy accelerated particles is present in the Orion region, most likely enriched in C and O. The interpretation of spectral features with line splitting is severely hampered by the current lack of sufficient laboratory measurements, which are largely limited to the 4.4 MeV line of \( ^{12}\text{C} \), but even here far from complete.

The appearance of the high-energy (> 100 MeV) gamma-ray sky is dominated by diffuse emission from the Galactic disk, originating from \( \pi^0 \)-decay following the interaction of high-energy (\( \gtrsim 1 \) GeV/nucleon) protons and nuclei with the interstellar gas. This emission (well mapped by the ESA COS-B satellite and the EGRET telescope aboard the CGRO) has provided the most direct means of studying the large-scale distribution of energetic particles in the Galaxy. Inverse Compton scattering of high energy electrons is another important contributor to the gamma-ray spectrum. At lower gamma-ray energies (about 1–100 MeV) electron bremsstrahlung dominates the gamma-ray continuum emission.

Energetic particles, i.e. cosmic rays (CR) that penetrate the solar system from deep space, leaves many open questions: (i) What/where are the sources, and (ii) what is their composition (electrons, protons, neutrons, alpha particles, heavier nuclei, their antiparticles, gammas, neutrinos, or possibly particles not producible in current accelerators)? The Galactic cosmic ray composition in the 10 MeV to 1 GeV range has been analysed in detail by the ESA-NASA Ulysses mission. Up to energies of some hundred TeV of particle energy it is possible to measure chemical abundances of cosmic rays directly on satellites or balloons. Nuclear spallation changes the original (primary) composition and is the dominant process for the rare isotopes of Li, Be, B in the interstellar medium, requiring better spallation cross sections near the particle thresholds [20]. There exists still controversy about the chemical composition above ~ 10\(^{15} \) eV. The spectrum of cosmic rays extends to energies beyond 10\(^{20} \) eV and obeys a
power law with a differential coefficient ranging between -2.7 (below $5 \times 10^{15}$ eV) and -3.1 (up to $3 \times 10^{18}$ eV), where it flattens out again.

![Graph showing cosmic ray flux at 1 TeV and relative abundance vs nuclear charge number Z.](image)

Figure 8.4: Composition of cosmic rays in comparison to solar system abundances (normalised to C). Spallation enhances the abundances of nuclei with low solar system values. The effect is energy dependent.

It has been proposed that cosmic ray particles can be attributed to three main sites of origin and acceleration, (i) supernova shocks in the interstellar medium, (ii) supernova shocks in the stellar wind of the progenitor star, and (iii) powerful radio galaxies with jets [21]. New CGRO(EGRET) data from supernova remnants indicate that CR’s follow a different power law ($\propto E^{-2.4}$) at their source of acceleration. In general, the search for the sources of charged CR’s is hampered by magnetic fields which destroy directional information, confining low energy cosmic rays to the Galaxy and leading to a shift from galactic to extragalactic origin with increasing energy, expected at $10^{18} - 10^{19}$ eV. Therefore, more energetic particles should provide a better information of their origin. However, their interaction with CMB photons limits the mean free path. The handful of observed events point towards areas within 50 Mpc, where few potential acceleration regions are known. The cut-off at high energies due the interaction with the CMB has been estimated at $5 \times 10^{19}$ eV (Greisen-Zatsepin-Kuzmin cut-off). The highest energies observed are at $3 \times 10^{20}$ eV (FLY’S EYE, AGASA, HAVERAH PARK, YAKUTSK). An alternative explanation for these particles might be that they are decay products of topological defects from the early universe. The study of these $>10^{20}$ eV events is therefore of great importance for universal particle models and the grand unification of the four forces.

Long-lived neutral particles like gammas ($<10^{-4}$ of the total flux) and neutrinos (flux fraction unknown) are not affected by magnetic fields. They reveal their origin more easily. Since 1989 high significance observations (5 - 35 $\sigma$) have identified 7 sources of high(est) energy gamma-rays in the range of 300 GeV up to 50 TeV [22]. The recent progress came by perfecting "Air Cerenkov" detectors. Interestingly, among the 7 sources, there are 3 extragalactic ones, the Active Galactic Nuclei (AGN’s) Mkn 421, Mkn 501 (WHIPPLE, HEGRA, CAT) and an Einstein source 1ES 2344+519 (WHIPPLE). The most recent discovery was episodic gamma-emission from the galactic micro-quasar GRS 1915. Three out of the seven sources show strong flaring, changing on timescales as short as hours. Thus, accelerations must take place in volumes of only a few tenths of light hours in contrast to model expectations. The gamma-production in all 7 sources can be explained by electron acceleration and inverse Compton scattering on low energy photons, with hadronic cascading being a viable competitor.

A completely different aspect of high energy gamma-astronomy is to make use of gammas to probe the presently unquantified infrared (IR) background (IRB). It might be possible that the IRB contains up to a few % of the CMB photon energy budget. Similarly to the CMB, the IRB is interacting with energetic gamma-rays. Therefore, the universe is not fully transparent to gammas in certain energy bands (at around $10^{15}$ eV the "gamma-visibility" extends barely to the centre of our Galaxy). Detailed mapping of the gamma-spectra of AGN’s at different red-
shifts will permit to map the distance at which gamma-rays reach us undisturbed. The IRB radiation is related to galaxy formation and thus deeply related to the question of dark matter.

Another long-lived neutral particle, the neutrino, can also be used to trace high energy sources. The weak interaction allows neutrinos to pass the IRB and CMB unabsorbed, but very large detector volumes are needed for their observation.

![VHE Gamma Sources (E > 300 GeV)](image)

Figure 8.5: Very high energy gamma-ray distribution, indicating point sources in and outside the Milky Way (pulsars, X-ray binaries, cataclysmic variables, a microquasar - stellar mass black hole - and extragalactic active galactic nuclei with massive black holes).

8.3 How to Proceed

In section 2 we gave an overview of astrophysical environments where aspects of nuclear and particle physics play a decisive role. Many of the ongoing efforts involving particle physics aspects have the nature of "observations" related to the early universe/big bang (dark matter searches, antimatter searches, CMB anisotropy), the solar neutrino problem (neutrino detectors with enhanced spectral and neutrino type information), supernovae and gamma-ray bursts (neutrino detectors, gamma-ray satellites), and cosmic rays (ground based high(est) energy CR, gamma and neutrino detectors). Laboratory and theoretical physics efforts in neutrino physics and dark matter related subjects are covered by the working group on neutrino physics and fundamental interactions. Cosmic Rays related laboratory efforts are not discussed here, but we refer to [20] for an overview on spallation cross section requirements. In the following we will describe ground-based efforts in neutrino (solar, supernova, cosmic ray) and high energy cosmic ray and gamma ray observations and then focus on nuclear physics aspects, requiring novel technical developments and new concepts in theory.

8.3.1 Neutrino detectors

The second-generation neutrino experiments in Europe focus on the low energy part of the solar neutrino spectrum. They are the Gallium Neutrino Observatory (GNO) and BOREXINO, both located at the Gran Sasso Laboratory. GNO is a continuation of GALLEX with improved technology and target mass. It will provide accurate information on the integral $\nu_e$-spectrum for $E_\nu > 233$ keV. BOREXINO concentrates on the detection of the 862 keV $^7$Be neutrino line by means of $\nu$-e scattering in a 100 t liquid scintillator target.

SUPERKAMIOKANDE and the 1000 t $D_2O$ Cerenkov detector at the Sudbury Neutrino Observatory (SNO) focus on the spectroscopy of the high energy part of the neutrino spectrum. SUPERKAMIOKANDE with its spectral shape information can give an unambiguous prove for neutrino oscillations by deviations from the expected $\beta$-spectrum. The SNO experiment provides information on neutral and charged current interactions with deuterium: $\nu + ^2H \rightarrow n + p + \nu$ and $\nu_e + ^2H \rightarrow p + p + e^-$. The first reaction is also sensitive to muon neutrinos and thus to neutrino oscillations. Both experiments will also be able to observe supernova neutrinos.

The challenging construction of large volume (up to a km$^3$ water or ice) high energy neutrino detectors has just begun. The European involvement is strong, both in the Lake Baikal (Russia) deep lake detector and in AMANDA, a south pole deep ice experiment. Furthermore, the NESTOR deep sea project near Pylos, Greece, and the French project ANTARES are in an early development phase.
8.3.2 Cosmic ray observations

The largest European CR activities are (from north to south): the KASCADE experiment at Karlsruhe (mainly aiming at solving the long standing question of the chemical composition above $10^{14}$ eV by performing high resolution large scale calorimetry, combined with precise electron and muon measurements in a scintillator matrix), the CAT detector, a recently started high performance air Cerenkov telescope in the French Pyrenees, the EAS-TOP installation on top of the Gran Sasso Laboratory, and the HEGRA experiment on La Palma, a combination of 6 air Cerenkov telescopes, a scintillator matrix, a wide angle Cerenkov array and Geiger towers for muon detection and some calorimetry. In addition, a British group operates large Cerenkov telescopes in Australia since 1979. Some groups participate in international activities, the most successful being an Irish-UK collaboration with the Harvard-Smithsonian groups operating the 10 m WHIPPLE air Cerenkov telescope.

The low expected flux of $>10^{20}$ eV CR’s (1 particle/100 square km/year) requires large detectors. Therefore, a large world-wide collaboration with a significant European participation is studying the construction of two 2500 km² detectors (one on the southern hemisphere in Argentina, one on the northern hemisphere in Utah), the so-called AUGER-project. Gamma-astronomy promises fast and rich results and quite a few new activities are under discussion. Solar farms open a door for quick and cost-effective experiments in the energy range below $3 \times 10^{11}$ eV but with modest gamma/hadron separation and also relatively small collection area (Celeste in the French Pyrenees, Graal at CESA I in Spain). The most ambitious plan is to build a 17 m Cerenkov telescope (MAGIC). This telescope, involving many new technologies, allows to explore the last ‘white spot’ in the energy scale between 20 GeV and 300 GeV with high efficiency. One expects to find between 100 and 1000 new gamma sources. These next generation experiments in earthbound gamma-ray astronomy will overlap with the next generation satellites and permit multiwavelength observations from radiowaves up to energies of at least $10^{14}$ eV.

8.3.3 Stable beams

The cross section $\sigma(E)$ of charged-particle-induced reactions drops nearly exponentially below the Coulomb barrier, $E_\text{c}$. Important reactions, like $^7\text{Be}(p, \gamma)^8\text{B}$, $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$, or $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$, are known down to limiting energies $E_l$ of 120keV, 190keV or 1MeV (mainly due to background effects of cosmic rays) and are applied to astrophysics at the relevant stellar thermal energy $E_\text{th}$ of 19keV, 39keV or 300keV [6]. The danger of such extrapolations down to e.g. $\approx 0.01E_\text{c}$ was demonstrated impressively in the case of $^2\text{H}(d, \gamma)^4\text{He}$, where new low-energy data changed the extrapolated values by a factor of 1000; other cases are $^9\text{Be}(p, \alpha)^6\text{Li}$ (factor 50) and $^{10}\text{B}(p, \alpha)^7\text{Be}$ (factor 200). Quite a number of $\sigma(E)$ measurements for the reactions in the pp-chain, the CNO-cycles, the NeNa- and MgAl-cycles in H-burning, alpha-induced reactions in He-burning and the s-process and heavy ion fusion reactions for the late phases of stellar evolution and type I supernova dynamics, have not yet reached the low-energy limit $E_l$, dictated by the cosmic ray background. These reactions can only be reliably investigated at high intensity, low energy accelerators with new and improved detection facilities, especially large, high granularity detector arrays for gammas and particle reaction products in conjunction with recoil separators.

If $E_l$ is reached experimentally and an extrapolation down to $E_\text{th}$ is uncertain, background free experimental facilities are needed. Passive shielding around the detectors provides a reduction of cosmic ray gammas and neutrons, but it produces an increase of gammas and neutrons due to the cosmic-ray interactions in the shielding itself. A $4\pi$ active shielding can only partially reduce the problem of cosmic ray activation. The background can be considerably reduced in a deep underground laboratory, like the existing solar neutrino experiments with similar counting rates of the order of 1 event per day or less. The world-wide first pilot experiment (LUNA, a Laboratory Underground for
Figure 8.6: The astrophysical S-factor for the reaction $^3\text{He}^*(^3\text{He,2p})^4\text{He}$. The filled circles were obtained by an underground pilot experiment (LUNA) at the Gran Sasso facility. The solid or dashed curves indicate the inclusion (non-inclusion) of screening corrections. The Gamov peak marks the energy range probed under solar burning conditions, reached for the very first time by experiment [23].

Nuclear Astrophysics) with a 50 kV accelerator at LNGS (Laboratori Nazionali del Gran Sasso, Italy) investigates presently the pp-chain reaction $^3\text{He}^*(^3\text{He,2p})^4\text{He}$ within the energy region of the solar Gamov peak (here $E_\alpha=21$ keV). The studies [23] provided for the first time data within the Gamov peak. Based on its success, larger accelerator facilities, ranging from a 200-400 kV single-ended accelerator up to a 2 MV tandem would offer the opportunity to investigate a wider energy range and spectrum of reactions. To cope with and make a most efficient use of the low counting rates requires the knowledge of resonance properties, obtainable via single or few particle transfer reactions, a task ideally suited for tandem accelerator facilities.

8.3.4 Screening effects

Nuclear reactions between two nuclei occur at a distance of the order of $10^{-13}$ cm after tunnelling the Coulomb barrier. Screening is related to the presence of target/projectile electrons in laboratory experiments or to the presence of other charged particles in a stellar plasma, which change the Coulomb barriers in comparison to bare nuclei. Thus, the screening problem for astrophysics has two aspects. (i) Laboratory screening has to be corrected in order to obtain the cross sections for bare nuclei, (ii) the stellar environment gives rise to screening effects in astrophysical plasmas as well, but under quite different conditions. In the laboratory, the targets and projectiles are usually neutral atoms/molecules and ions, causing a larger cross section, $\sigma_s(E)$, with an enhancement factor over bare nuclei $f_{\text{lab}}(E) = \sigma_s(E)/\sigma_0(E) \approx \exp(\pi\eta U_c/E)$, where $\eta$ is the Sommerfeld parameter and $U_c$ is the electron-screening potential energy. For $E/U_c < 100$, shielding effects become important for understanding and extrapolating low energy data. The observed enhancements in recent low-energy studies of several fusion reactions might be larger for some reactions than could be accounted for from available atomic-physics models [24]. As the stopping power corrections at these low energies enter strongly into the determination of the bombarding energy for $\sigma(E)$, and they are quite uncertain, additional efforts must also provide energy-loss data far below the Bragg peak, since such data (not available in the literature) influence sensitively the analysis of the fusion cross sections.

In astrophysical environments which permit nuclear reactions, nuclei are fully ionized, but polarisation of the electron cloud around nuclei or the Coulomb lattice effects of electrons and ions have to be accounted for. For instance, in the case of a pure carbon plasma with a density $\rho = 10^9$ g/cm$^3$ and a temperature $T = 10^9$ K, the rate of the reaction $^{12}\text{C} + ^{12}\text{C}$ increases by a factor $10^{10}$ due to the influence of the surrounding particles. Usually, the screening factor is written as $f=r/\tau_b=\exp(U/kT-\Phi)$, where $r$ and $\tau_b$ are the rates with and without (bare nuclei) the inclusion of screening, $U$ corresponds to the Coulomb corrections to the purely nuclear Q-value, and $\Phi$ is due to the different radial behaviour of the potential. The weak and strong screening regimes are described by the conditions $|f-1| << 1$ and $|f-1| >> 1$ (see [25] for detailed discussions). $U/kT$ is always dominant, but $\Phi$ becomes non-negligible for the strong screening regime. If densities are high enough, the barrier penetration is driven by the energy of ground state lattice oscillations of the nuclei rather than the thermal energy, defining the so called pycnonuclear regime.
The theory of the weak screening regime has been considered satisfactory, since corrections are usually smaller than the current uncertainties in many rates. For the strong screening regime the results are a bit controversial but seem to converge. Question are related to the (non-uniform?) density distribution of the degenerate electrons. The evaluation of the reaction rate in the pycnonuclear regime is quite complicated since the thermal distribution of nuclei is no longer given by a Boltzmann distribution. Two limiting cases have been traditionally used: (i) the "static" case, that assumes that all the nuclei and the center of mass of the reacting particles are frozen in their equilibrium positions and (ii) the "relaxed" case, that assumes that the position of the centre of mass is fixed and the remaining lattice points polarise into the positions determined by the separation of the two reacting nuclei. Monte-Carlo simulations of the interparticle potential seem to indicate that the relaxed approximation is the correct one, but the proper accounting of the polarisation energy gives a final fusion rate very near to the static one. Thus, the understanding of the dynamics of the crystal needs further investigation as well as the transition from the strong screening to the pycnonuclear regime.

### 8.3.5 Neutron beams

There has been considerable progress over the last 20 years in studying neutron-induced reactions, primarily for understanding and interpreting s-process nucleosynthesis, where the Karlsruhe group (FZK) played a leading role [8]. The experiments rely on different methods of producing the neutrons in the appropriate energy range, either the use of thermal neutrons produced at reactors, which can be utilised to measure the s-wave component of the cross section, or the use of low energy neutron beams for the measurement of possible p-wave or higher energy resonant contributions. Two complementary methods are presently used to provide neutrons at stellar energies. The first method is based on time of flight techniques (TOF) at modern accelerators in connection with neutron sources producing a wide neutron energy range from nearly thermal energies up to energies in the MeV range. The second method is based on neutron energy spectra which simulate a stellar \( (kT \approx 25\ \text{keV}) \) Maxwell-Boltzmann distribution, typically produced by \(^7\text{Li}(p, n)^7\text{Be}\) or similar light-particle-induced reactions at low energy, high intensity Van de Graaff accelerators. The on-line detection of the reaction products is often limited by high neutron fluxes. Therefore, the activation technique is used frequently, measuring the characteristic decay of the reaction product, in case it is radioactive [26]. Otherwise new on-line detection techniques have to be used for capture \( \gamma \)-radiation at high neutron fluxes (arrays of BaF\(_2\) detectors less sensitive to neutron radiation, e.g. the Karlsruhe 4\(\pi\)-detector, or heavily shielded NaI detectors). The recently developed high granularity Ge clover or cluster detectors are highly suitable for future on-line (\(n, \gamma\)) measurements.

Future efforts should include the simulation of stellar neutron spectra for lower temperatures \((kT = 8\ \text{keV} \) rather than at 25 keV\) and the further development of detector systems for on-line and off-line investigations. Targets of interest are light and intermediate mass isotopes with their limited amount of available data, the branching point nuclei, requiring the production of long-lived radioactive targets for off-line neutron capture studies (like \(^{79}\text{Se}, ^{85}\text{Kr}, ^{95}\text{Zr}, ^{107}\text{Pd}, ^{135,137}\text{Cs}, ^{141}\text{Ce}, ^{147}\text{Pm}, ^{151}\text{Sm}, ^{156}\text{Eu}, ^{169}\text{Er}, ^{170}\text{Tm}, ^{175}\text{Yb}, ^{186}\text{Re}, ^{204}\text{Tl}, ^{193}\text{Pt}\), and remeasurements for \(^{93}\text{Zr}\), and \(^{99}\text{Tc}\)), and cross sections of thermally-excited low-lying isomeric states (e.g. \(^{103}\text{Rh}, ^{119}\text{Sn}, ^{169}\text{Tm}, ^{187,188}\text{Os}, \) and \(^{193}\text{Pt}\)). For determining the endpoint of the s-process, neutron capture measurements are needed on the long-lived radioactive \(^{210}\text{Bi}\) in its ground and isomeric state and the ground state of \(^{210}\text{Po}\).

### 8.3.6 Radioactive beams

In explosive astrophysical environments nuclear burning times are (much) shorter than seconds and unstable nuclei will undergo further reactions. Among charged-particle reactions \((p, \gamma)\) and \((\alpha, \gamma)\) capture reactions dominate. Due to the high \(T\) temperatures, the relevant thermal energies \(E_0\) are close to the Coulomb
barrier $E_c$, where $\sigma(E)$ is often of the order of $\mu$b and more. For short-lived nuclides, the only direct method for $\sigma(E)$ measurements is the production of radioactive nuclides in a first reaction, separation of the relevant nuclei, and acceleration of a radioactive ion beam (RIB) with typically 1 pA currents, interacting with hydrogen or helium gas targets (inverse kinematics). A 10 pA RIB current, a cross section of 10$\mu$b, and a gas target density of 10$^{19}$ atoms/cm$^2$ cause 23 capture reactions per hour. A growing number of laboratories have already produced low energy RIB’s of astrophysical interest or are in the stage of technical development: ARENAS/Louvain-la-Neuve, SPIRAL/GANIL, REX-ISOLDE/ CERN, EXCYT/Catania, PIAFE/ILL, TWINSSOL/Notre Dame, HRIBF/ORNL, ISAC/TRIUMF, ATLAS/ANL.

(\alpha,p) (p,\alpha) Si Al Mg Na K Ne Ar F \beta^{+}\nu O N C B Li He N

structure extended to $^{48}$Ca

Figure 8.7: The hot CNO-cycle with breakout reactions to Ne. From Ne to Ca similar hot cycles exist, based always on alpha-nuclei like $^{20}$Ne, $^{24}$Mg etc.

In inverse kinematics, the detection of the capture $\gamma$-rays or of the residual nuclides (via their radioactive decay signals) leads in general to efficiencies far below 100%. In addition, radioactivity hampers seriously the detection methods. Only $p^{(13)}N,\gamma)^{14}$O has been successfully studied so far via $\gamma$-ray spectroscopy (using an array of Ge detectors at Louvain-la-Neuve) because of an exceptionally large cross section due to a strong and broad resonance. For all other capture reactions studied so far, only upper limits could be derived at the relevant energies, predominantly due to a more typical (i.e. small) cross section. The measurements require a significantly improved detection efficiency, achievable by recoil mass separators (RMS) which filter the RIB from the recoil capture nuclides and focus all recoils for their identification. The RIB-suppression factor must be 10$^{-10}$ or better (e.g. 10$^{-16}$ for $\sigma(E)$ = 1 pb). The potential use of a RMS was successfully exploited in the study of $p^{(12}C,\gamma)^{13}$N and $p^{(^{7}Be,\gamma)^{8}}$B [27] at Naples, and beam suppression factors up to 10$^{-16}$ (European Recoil separator for Nuclear Astrophysics, ERNA) seem feasible. Going beyond radiative captures will require RIB facilities with detection systems for protons and neutrons. Efficient detection systems for charged particles have been developed in recent years, with a high suppression of the background created by RIB’s (e.g. LEDA, the Louvain-Edinburgh-Detector-Array).

It should be pointed out that the capture reactions $^{13}$N($p,\gamma)^{14}$O and $^{7}$Be($p,\gamma)^{8}$B have also been studied using the method of Coulomb dissociation at RIKEN and GSI. The measurements via $^{14}$O($\gamma,p)^{13}$N and $^{8}$B($\gamma,p)^{7}$Be provide information of the radiative-capture cross section to the ground-state of the compound nucleus [28]. The first reaction, which led to a precise result, represents (again) an "ideal" case due to a broad and strong resonance excited to 100% by E1-radiation. There exist still uncertainties about the obtainable precision. Experimental as well as theoretical problems (high energy resolution of the RIB, nuclear interference and post-acceleration effects) might ask first for a test and calibration of this method with reactions, where high accuracy direct measurements are already known. Because of its strong potential for reactions where direct cross section measurements are extremely difficult, this method should be further explored, also making use of different RIB energies. Some reactions can only be studied via the Coulomb dissociation method. Examples are the sequence of two
capture reactions with an intermediate particle-unstable nucleus, similar to the triple alpha process $^4\text{He}(2\alpha, \gamma)^{12}\text{C}$ in He-burning. $(2p, \gamma)$ reactions can permit a faster reaction flow at high stellar densities by connecting “peninsulas” of the proton-drip line [15]. Others are the $^4\text{He}(\alpha n, \gamma)^{19}\text{Be}$ and $^4\text{He}(2n, \gamma)^{16}\text{He}(2n, \gamma)^{8}\text{He}$ reactions, bridging the mass 5 and 8 instability gaps. Similarly, the study of $(n, \gamma)$ reactions on unstable nuclides is another unique application.

8.3.7 Nuclear structure

Other working groups have outlined the key issues of nuclear structure far from stability and their experimental exploration with RIB facilities. Here we will focus on astrophysical aspects via mass and beta-decay measurements with RIB’s involving neutron-rich and proton-rich nuclei [29]. Mass measurements reflect shell structure, deformation and pairing correlations. In $(n, \gamma) - (\gamma, n)$ or $(p, \gamma) - (\gamma, p)$ equilibrium conditions, as they are approached in the r- and rp-process, neutron or proton separation energies with a precision of about 100 keV are required for astrophysical applications and should be extended to lifetimes, preferably as small as ms. The properties of near proton drip-line isotopes are necessary to determine the rp-process reaction path in the mass range $A \geq 56$. Of particular interest are measurements of masses, beta-decay half-lives and beta-delayed proton emission along the $N=Z$ line, possibly extending up to $Z=50$. Such experiments can be performed at fragment separator facilities for radioactive beams like GANIL/LISE, GSI/ESR, NCSL/MSU or RIKEN. Regions where the r-process path comes closest to stability and causes three abundance maxima are located at the closed neutron shells $N=50$, 82, 126 for $A$ 76-82, 128-132, 190-196. $N=50$ and 82 have been reached for $A=79.80$ and 129,130 by experiments at CERN-ISOLDE. The knowledge of beta-decay half-lives and delayed neutron emission were very helpful in interpreting the relation to solar abundances.

Characteristics of the shell structure further from stability are most influential, leading to questions whether for very neutron-rich nuclei the shell gap at $N=82$ is less pronounced (i.e. quenched) than predicted by global macroscopic-microscopic mass models like the Finite Range Droplet Model (FRDM) or the Extended Thomas Fermi approach with Strutinski Integral (ETFSI) [30]. This has an important effect on the r-process path and the resulting abundances below the $A=130$ peak. An experimental investigation of shell quenching along $N=50$ and 82 towards lower Z’s (and reaching the r-process path at $N=126$ for the very first time) is a highly desirable goal. It will test the nuclear structure responsible for the abundances of heavy nuclei, improve the understanding how well microscopic-macroscopic models, self-consistent microscopic approaches or relativistic mean field theories can describe reality and lead to an extensive test of effective forces used for such calculations [31]. The theoretical studies of nuclear $\beta$-decay properties are based on the spectral distribution of the $\beta$-decay transition probability (the $\beta$-strength function). For the short-lived nuclides on the r- and rp-process paths, the approximation of allowed Gamov-Tellec: (GT) transitions is usually accurate enough. Microscopic models like the proton-neutron quasiparticle random phase approximation (QRPA) are generally used, based on empirical or self-consistent one-body single-particle potentials, a pairing interaction, and a spin-isospin effective NN-interaction [32]. Thus,

Figure 8.8: The rp-process path, including 2p-captures, for temperatures of $1.9 \times 10^{10}$K and densities of $10^{11}g/cm^3$ [31]. Also shown are stable nuclei and the position of the proton-drip line.
this approach is based on single-particle spectra and their uncertainties. Therefore, beta-decay properties are another testing ground for self-consistent mean-field approaches which can be significantly improved if the form and parameters of the corresponding density functionals or effective forces are fitted not only to the nuclear ground state properties near the stability, but also to those of doubly-magic unstable nuclides. Further studies in the regions of $^{78}\text{Ni}$ and $^{132}\text{Sn}$ at RIB facilities and high-flux nuclear reactors will be extremely hel

![Figure 8.9: The r-process path at a neutron separation energy $S_n \approx 3$ MeV][32].

Explosive nuclear burning also requires the ability to predict reaction cross sections with the aid of theoretical models. Especially for light nuclei, microscopic cluster models can be applied [33]. A high level density in the compound nucleus at the appropriate excitation energy allows to make use of the statistical model approach. For the majority of nuclei in astrophysical applications the necessary experimental information (on e.g. optical potentials for particle and alpha transmission coefficients, level densities, resonance energies and widths of giant resonances – to be implemented in predicting E1 and M1 gamma-transitions) is not available. The real challenge is thus to predict all these necessary ingredients [14]. Standard spectroscopic methods can be utilised in connection with RIB’s to assess level densities and giant resonance properties, scattering experiments for determining optical potentials.

### 8.3.8 Weak interactions

Electron captures sample a larger fraction of the Gamow-Teller strength function than beta-decays, due to the high electron Fermi energies in late phases of stellar evolution, stellar collapse, and in explosive events like type Ia and II supernovae. Such environments contain a number of unstable fp-shell nuclei, among them $^{55-60}\text{Co}$, $^{56-61}\text{Ni}$, $^{54-58}\text{Mn}$, and $^{54-59}\text{Fe}$. They can be studied via charge-exchange reactions using radioactive nuclear beams. Astrophysical tabulations based on shell model matrix elements are only available for light nuclei in the sd-shell. For heavier nuclei, more simplified approaches based on average positions of the Gammon-Teller giant resonance and average matrix elements have been utilised until now. A new Monte-Carlo shell model technique allows calculations in the fp-shell (and at finite temperatures) and reproduces the measured GT$_+\text{-}$distribution very well. As a next step this method should be applied to those nuclei which cannot be measured with current techniques [34].

Neutrino induced transmutation of nuclei play an important role in type II supernovae. The intense neutrino flux leads to heating via neutrino and anti-neutrino captures on neutrons and protons and inelastic neutrino scattering on nuclei. The latter could affect the outcome of the r-process by neutrino spallation of neutron-rich nuclei and produce also a significant amount of rare isotopes like $^7\text{Li}$, $^{11}\text{B}$, $^{19}\text{F}$, or $^{180}\text{Ta}$ (neutrino-nucleosynthesis). These processes require neutrino-nucleus cross sections. Since 1990 accelerator-based measurements of neutrino induced reactions on nuclei have become feasible (KARMEN, LSND) [35] (see the working group on neutrino physics and fundamental interactions). Neutrino sources in these experiments provide (as one component) monoenergetic $\nu_\mu$ (29.8 MeV) neutrinos and $\nu_e$ and $\bar{\nu}_\mu$ with continuous energy spectra up to 52.8 MeV, similar to the neutrino energies in supernovae. Theory can be tested with such measured cross sections, complementary data
from other weak interactions in nuclei like beta-decay and muon capture rates, and even electron scattering data, as the weak and electromagnetic interactions are related. The Continuum Random Phase Approximation (CRPA), which combines the usual RPA treatment with a correct description of the particle states in the continuum [36], has passed these tests, provided a good description of the giant (dipole and spin-dipole) resonances in $^{12}$C and $^{16}$O, and has been found to reproduce well the total muon capture rates in nuclei like $^{12}$C, $^{16}$O, and $^{40}$Ca. Future neutrino experiments at the European Spallation Source (ESS) would offer unique possibilities to further explore neutrino properties and interactions with nuclei.

8.3.9 Dense nuclear matter

The discovery of neutron stars (NS's) in the form of pulsars has been a major stimulus to studies of dense matter. According to our present understanding, neutron stars have a rich structure. The outermost layers are rather similar to terrestrial crystalline matter. With increasing depth in the star, and thus increasing density, nuclei become more neutron-rich until at a density of about one thousandth of nuclear nuclear density, nuclei reach the neutron drip line. At higher densities nuclei coexist with a neutron liquid, and they eventually dissolve just below nuclear density. Key questions concern the equation of state of matter as a function of density, temperature, the total proton/nucleon ratio $Y_e$, the weak interaction rates shifting $Y_e$ to its equilibrium value, and neutrino emission processes.

The quest to understand the interiors of these objects, which are much denser and more neutron-rich than laboratory nuclei, led to the development of many-body techniques able to treat strong correlations. An important achievement of the past two decades is that there is now a remarkably good agreement among the various microscopic calculations of the properties of dense neutron matter up to about nuclear matter density. The results are essentially independent of the many-body technique and the two-body nucleon-nucleon interaction, provided the latter fits nucleon-nucleon scattering data. Close to nuclear matter density, nuclei may be rod-like or plate-like. This was first realised in the context of stellar collapse, but has now been shown to be important also for neutron stars. These phases are potentially very important for understanding a number of aspects of neutron star behaviour, especially the sudden jumps in the rotational frequencies observed in a number of pulsars [37]. To understand nuclear phenomena in neutron-rich matter one needs more reliable effective interactions. Microscopic many-body calculations of finite systems can be used to improve models of effective interactions. At the present time it is possible, with the Green's function Monte-Carlo method, to make essentially exact calculations of the energy of nuclei up to $A=7$ and for systems of up to 8 neutrons. For larger systems, good estimates of properties can be obtained using the cluster variational Monte Carlo method. These methods are now beginning to yield important contributions. In particular, for pure neutron systems the spin-orbit interaction is found to be suppressed by about a factor of two in comparison to symmetric nuclear matter.

Matter at densities above nuclear density occurs both in the interiors of cold neutron stars as well as in stellar collapse (e.g. supernovae) or neutron star mergers. In the laboratory, collisions between heavy ions are the only direct way of studying the properties of dense matter. In this case matter is roughly isospin symmetric, and has zero strangeness. The situation is different in neutron stars, because the lifetime is very large compared with weak interaction times, i.e. $Y_e$ is much less than that in laboratory nuclei. At high densities matter consists of interacting baryons (neutrons, protons, and possibly hyperons and other particles) and/or quarks in beta-equilibrium with leptons. In addition, Bose condensates of pions or kaons may be present. The key problems are to understand the interactions between possible constituents and develop reliable techniques for calculating the properties of a strongly-correlated, relativistic system of hadrons [38]. This is crucial, because 95% of the matter in a neutron star is located in regions with
supranuclear densities, where different equations of state "on the market" can vary strongly and lead to maximum neutron star masses ranging from 1.4 to roughly 2.8 M\(_\odot\). There exists a growing group of milisecond pulsars (rotating neutron stars with periods below 10 ms). The finding of rotation periods less than 1 ms would challenge present models.

Another crucial area is that of neutrino processes in neutron stars and in matter in a collapsing star. Emission of neutrinos is the dominant mechanism for loss of heat from a neutron star during the first \(10^5 - 10^6\) years of its life, and the measurement of the surface temperatures of neutron stars provides a way of probing neutrino processes in the star. Since neutrino emission rates are very sensitive to the constituents of dense matter, such measurements are a promising way of gleaning information about the deep interiors of neutron stars. In addition to the neutrino emission, absorption and scattering processes discussed in 2.3 and 3.7, the effects of correlations in matter needs to be further explored.

### 8.4 Summary

Our working group had the task to discuss the present status and future prospects of nuclear and particle astrophysics, a field which addresses quite diverse question like e.g. the big bang, stellar evolution, supernovae, neutron stars or cosmic rays (see also [39]). Section 3 outlined the open problems and future needs and means for their exploration. Many of these benefit directly or indirectly from the overall recommendations accepted by NuPECC in April 1997, e.g. (i) the need to preserve and maintain low energy/high intensity stable beam accelerators with novel gamma and particle detection systems, (ii) the support for existing and need for next generation (low and high energy) radioactive beam facilities to provide reaction cross sections of unstable nuclei and explore nuclear structure far from stability towards the neutron and proton drip-lines, (iii) to support an expansion of the pilot underground (background-free) accelerator facility at Gran Sasso for the direct measurement of cross sections at stellar thermal ener-gies much below the Coulomb barrier, (iv) to support present and next generation solar neutrino detectors, (v) continued R&D in cryogenic detectors for double beta-decay and dark matter searches, (vi) relativistic heavy ion collisions which might improve our understanding of the supra-nuclear equation of state, (vii) the need for positions in theory to push ahead the complex questions behind these experimental investigations and (vii) finally the need for powerful computing facilities to address the complex many-body problems and large scale hydrodynamical modeling. It is our hope that other communities (particle/high energy physics, astronomy, space research) give support for the equally important topics outlined in the sections on CMB anisotropies, the baryon asymmetry of the universe, high energy cosmic ray, gamma ray and large volume neutrino detectors, gamma-ray satellites, and observational tools to determine the composition of stars, the interstellar and intergalactic medium.

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9. Neutrino Physics

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9.1 Introduction

Neutrino experiments are at the forefront of the physics because they offer one of the few opportunities at low and intermediate energies to probe the constituents of matter and their interactions. Within the standard model neutrinos are taken to be massless with no electromagnetic interactions and with only two degrees of freedom for each of the e, μ, and τ family. There is no unambiguous empirical evidence in conflict with this simple picture, but also, there are no fundamental symmetries that would explain this baffling simplicity. The observation of neutrino masses, electromagnetic interactions, or the “missing” right-handed components would constitute the long-sought evidence for “physics beyond the standard model.”

Neutrino masses in the 1–50 eV range would play an important role for cosmological structure formation (Sec. 9.8). However, the bulk of the cosmic dark matter probably consists of some novel weakly interacting species such as the supersymmetric “neutralinos.” In many phenomenological ways they resemble massive Majorana neutrinos and are thus included in this report (Sec. 9.8).

There are only few efforts to search for anomalous electromagnetic neutrino couplings because the existing astrophysical limits indicate that it will be very difficult to detect such properties (Sec. 9.2). On the other hand, neutrino magnetic dipole or transition moments would have important consequences in supernovae or the early universe, and they would provide clear evidence for physics beyond the standard model.

The holy grail of neutrino physics is the quest for their masses. Direct experimental limits are obtained from the phase-space modification of reactions with final-state neutrinos (Sec. 9.9). A far more restrictive constraint of around 50 eV on all flavours obtains from cosmology (Sec. 9.2). This bound applies if neutrinos do not decay fast on cosmological time scales. This possibility requires neutrino interactions beyond the standard model. Thus it appears unlikely that neutrino masses can be discovered by direct kinematical methods with the exception of νe (Sec. 9.9).

It is conceivable that νμ and ντ masses in the 10 eV regime can be measured from signal dispersion effects of a future galactic supernova (Sec. 9.2). Other than that one must rely on indirect methods to search for neutrino masses below the cosmological limit.

The first approach relies on nuclear double beta decay. Recently it has become possible to measure the 2ν2β mode in several cases. The unobserved neutrinoless (0ν2β) mode requires the violation of (electron) lepton number by two units. A Majorana mass term would have this effect with an amplitude proportional to m_ν_e_Majorana. Current m_ν_e_Majorana limits are in the neighbourhood of 1 eV (Sec. 9.7).

This method requires a neutrino Majorana mass term while all charged fermions have Dirac masses. It is natural, however, to think of Dirac fermions as a pair of mass-degenerate Majorana ones. The absence of the electromagnetic gauge coupling for neutrinos obviates the need for them to be mass degenerate. The unobserved (right-handed) partner could well be very heavy, perhaps with a mass at the grand unifica-
tion scale. The small masses of the active (left-handed) states are then natural in the framework of the see-saw mechanism.

If neutrinos do have masses the flavours probably mix in analogy to the quarks. For example, the electron neutrino would be a superposition of three mass eigenstates \( m_j \),

\[
|\nu_e\rangle = \sum_{j=1}^{3} U_{ej} |\nu_j\rangle
\]

(9.1)

with the mixing amplitudes \( U_{ej} \). In this case, what the \( 0\nu\beta\beta \) experiments really measure is the quantity \( (\nu_\nu) = \sum_j |\lambda_j| U_{ej}|^2 m_j, \text{Majorana} \) where \( \lambda_j \) is a CP phase equal to \( \pm 1 \), and the sum is to be extended over all two-component Majorana neutrinos that mix with \( \nu_e \).

Another consequence of neutrino mixing is the phenomenon of flavour oscillations which is the most important indirect method to search for neutrino masses. A neutrino produced as a \( \nu_e \) is generally a superposition of three mass eigenstates. Along a beam (z-direction) each of them acquires a phase according to the plane-wave propagation with \( e^{-i(Ev/c - p_{\nu \cdot z})} \). Because \( p_{\nu} = (E_{\nu}^2 - m_{\nu}^2)^{1/2} \) the different mass components acquire different phases so that downstream one finds a new superposition. One distinguishes between appearance experiments where one searches for a neutrino flavour different from the one produced at the source, and disappearance experiments where a flux depletion of the originally produced flavour is looked for.

In general, \( U \) is a \( 3 \times 3 \) matrix, or even larger if one speculates that new (sterile) neutrino flavours exist. A general discussion of neutrino oscillations is thus quite complicated. We limit our presentation to two-flavour mixing, keeping in mind that a definitive interpretation of experimental results may require more complicated assumptions.

Taking \( \nu_e - \nu_\mu \) mixing as an example, the interaction eigenstates are expressed as

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
\end{pmatrix}
\]

(9.2)

in terms of the mass eigenstates \( |\nu_1\rangle \) and \( |\nu_2\rangle \), and in terms of the mixing angle \( \theta \). The probability for an original \( \nu_e \) to appear as a \( \nu_\mu \) is

\[
p(\nu_e \to \nu_\mu) = \sin^2(2\theta) \sin^2(\pi L/\Delta m_{\nu} \text{osc})
\]

(9.3)

where \( L \) is the distance from the source and

\[
\Delta m_{\nu} \text{osc} = \frac{4\pi E_{\nu}}{\Delta m_{\nu}^2} = 2.48 \text{ m } \frac{E_{\nu}}{1 \text{ MeV}} \frac{1 \text{ eV}^2}{\Delta m_{\nu}^2}
\]

(9.4)

is the oscillation length with \( \Delta m^2 = m_2^2 - m_1^2 \).

Depending on the source and the detector distance, different experimental techniques are needed to cover various areas in the \( \sin^2 2\theta - \Delta m^2 \)-parameter space. Besides accelerator neutrino beams (Sec. 9.3) and reactors (Sec. 9.4), both solar (Sec. 9.5) and atmospheric neutrinos (Sec. 9.6) have turned out to be extremely important. They exhibit signal characteristics that can be consistently interpreted by oscillations.

When the neutrino beam passes through matter, notably in the case of solar and atmospheric neutrinos, the medium modifies the vacuum dispersion relation. The neutrino refractive index depends on the flavour because normal matter contains many electrons but no muon or tau-leptons. This flavour birefringence modifies the effective mixing angle and effective \( \Delta m^2 \) as a function of matter density. When these effects are important one speaks of\( \text{ matter oscillations, otherwise of vacuum oscillations.} \)

In the Sun, the neutrinos are produced near the center and thus have to pass through a density gradient before they reach the surface. In this case it can happen that the effective \( \Delta m^2 \) changes sign along the beam, leading to so-called resonant oscillations or the MSW effect. In this situation one must go beyond the simple oscillation probability Eq. (9.3). One can obtain an almost complete flavour conversion even for small mixing angles without parameter fine tuning.

The experimental activities on the neutrino physics are carried out at reactors and high energy accelerators, in underground and small scale laboratories. A large part of these activities concern topics pertaining the nuclear physics.

Some experiments, such as the double beta decay and the beta decay to search for the neutrino mass, involve directly the nucleus. Some
others use experimental techniques typical of the low energy physics as the study of solar neutrinos and dark matter, and the experiments at the reactors.

The understanding of the neutrino physics are of fundamental interest not only in the elementary particle physics but also in nuclear physics. Therefore all activities focused to fix the open problems are of great interest for both these fields.

9.2 Astrophysical Limits

Neutrinos play a major role in astrophysics and cosmology, and conversely one can derive some of the most restrictive limits on their properties. We mention only some of the most outstanding results.

9.2.1 Neutrino Masses

In the big-bang scenario of the early universe one expects about as many “blackbody neutrinos” as the measured density of cosmic microwave photons. In units of the critical density one infers a neutrino cosmic energy density of \( \Omega_\nu h^2 = \sum_{i=1}^{3} m_i / 93 \text{eV} \), where \( h \) is the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\). The observed age of the universe together with the measured expansion rate yields \( \Omega h^2 \leq 0.5 \) so that

\[
m_\nu \lesssim 50 \text{eV}
\]

for any flavour. If one of the neutrinos had a mass near this bound it would provide a significant fraction of the cosmic dark matter.

Theories of cosmological structure formation disfavour “hot dark matter” (e.g. neutrinos). However, “cold dark matter” (e.g. neutralinos) overproduce structure on small scales, a problem that can be patched up in a “mixed dark matter” scenario with \( \sum_{i=1}^{3} m_i = 5 \text{eV} \). Even a “sub-critical” neutrino mass is cosmologically interesting!

Besides relying on the standard big-bang picture, Eq. (9.5) depends on the assumption that neutrinos do not decay fast on cosmological time scales. The dominant standard-model decays of mixed neutrinos are \( \nu \to \nu' \gamma \) or \( \nu \to \nu' \gamma \gamma \) which are far too slow to invalidate Eq. (9.5). In addition, radiative decays have been constrained from the absence of anomalous cosmic photon backgrounds in various energy bands.

The experimental \( \nu_\tau \) mass limit exceeds \( 2 m_\chi \) so that \( \nu_\tau \to \nu_\tau e^+e^- \) is possible, and could be fast enough to invalidate Eq. (9.5). However, \( \gamma \) rays for the inner Bremsstrahlung process \( \nu_\tau \to \nu_\tau e^+e^- \gamma \) have not been observed by the SMM or COMPTEL satellites from SN 1987A, providing very restrictive limits on this process.

One infers that all three sequential neutrinos must obey Eq. (9.5) unless they decay fast into “invisible” channels by non-standard couplings. Turning this around, experimental searches for neutrinos with masses exceeding Eq. (9.5) are tantamount to searching for novel neutrino couplings beyond the standard model.

The \( \bar{\nu}_e \) signal duration of SN 1987A yields a limit on dispersion effects. In particular

\[
m_{\nu_e} \lesssim 20 \text{eV}, \tag{9.6}
\]

somewhat less restrictive than the corresponding laboratory limits from tritium \( \beta \) decay.

The best direct mass limits could be obtained from a future Galactic SN if the neutrino signal is measured in a detector like Superkamiokande in conjunction with the proposed Supernova Burst Observatory (SNBO). Optimistically, one may be able to achieve a sensitivity down to the 10 eV range even for \( \nu_\mu \) and \( \nu_\tau \).

9.2.2 Neutrino Oscillations

The \( \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau \) supernova fluxes are believed to have different spectra. Therefore, if neutrino oscillations would partially “swap” the flavours, the interpretation of the SN 1987A signal would have to be modified, especially if one of the large-angle solutions to the solar neutrino problem (Sec. 9.5) were found to obtain.

Resonant oscillations may occur in a SN between \( \nu_e \) and \( \nu_\mu \) or \( \nu_\tau \). For mass differences between a few eV to about 100 eV, the matter-induced conversion would occur so close to the neutrino sphere that SN physics itself
would be modified. The increased $\nu_e$ energies would help to transfer energy to the stalling shock wave and thus help to explode SNe in the delayed-explosion scenario. Conversely, the spectral swap would cause the $\nu_e$ spectrum to be stiffer than the $\bar{\nu}_e$ one, so that the neutrino-driven wind from the new-born neutron star is shifted into a proton-rich phase, preventing the r-process nucleosynthesis which is thought to occur in this environment. There is a range of mixing angles in the rough range $10^{-7} \leq \sin^2 2\theta \leq 10^{-8}$ where the MSW effect could help to explode SNe, and yet not disturb r-process nucleosynthesis.

### 9.2.3 Electromagnetic Properties

A neutrino electromagnetic dipole or transition moment would lead to an enhanced rate for the plasma decay process $\gamma \rightarrow \nu \bar{\nu}$ which dominates the neutrino cooling of low-mass stars, notably of low-mass red giants before the helium flash. This would delay helium ignition, in contradiction with globular-cluster data, leading to

$$\mu_\nu \leq 3 \times 10^{-12} \mu_B$$  \hspace{1cm} (9.7)

with $\mu_B = e/2m_e$ the Bohr magneton. This limit applies if $m_{\nu_\mu}, m_{\nu_\tau} \leq 5$ keV where threshold effects become important.

Transition moments can be constrained by searching for radiative decays $\nu \rightarrow \nu'\gamma$. If $\nu'$ is essentially massless the decay rate is $\mu_{\nu}^2 m_{\nu}/8\pi$ with $\mu_{\nu}$ the transition moment. If neutrinos obey Eq. (9.5) the phase-space factor $m_{\nu^2}$ renders the radiative decay limits from reactor, accelerator, solar, supernova, and cosmic background neutrinos less restrictive than Eq. (9.7).

### 9.3 Neutrino physics at accelerators

Presently the main goal of experiments with neutrino beams from high energy accelerators is the search for neutrino oscillations.

#### 9.3.3 Standard physics experiments

Two experiments are presently running at the Fermilab 800 GeV Tevatron.

NuTeV uses a neutrino beam from the decay of sign-selected hadrons, which allows to unambiguously distinguish $\nu$ and $\bar{\nu}$ interactions. With such a beam, the measurement of the cross-section ratio between neutral-current and charged-current neutrino-nucleon interactions leads to a precise determination of the weak mixing angle, $\sin^2 \theta_W$, and also to a precise measurement of the parameter $\rho$ which describes the ratio of neutral to charged-current coupling strengths. NuTeV will measure $\sin^2 \theta_W$ with an expected total error of $\pm 0.0025$ and $\rho$ with an error of $\pm 0.010$. Within the electroweak theory these measurements can be expressed in terms of equivalent measurements of the top quark and W boson masses. Any significant difference between the NuTeV results and direct measurements of the top and W masses would provide indirect evidence for new physics.

Experiment E-872 (DONUT, for Direct observation of NU-Tau) aims at the first observation of $\nu_\tau$ charged-current interactions. D$_S$ mesons produced by the interactions of 800 GeV protons in a beam dump decay to $\nu_{\tau}$'s which are detected by observing $\tau$ production and subsequent decay in an emulsion target.

#### 9.3.2 Searches for Neutrino Oscillations

**The LSND experiment**

The Liquid Scintillator Neutrino Detector (LSND) has recently reported the observation of events which can be interpreted in terms of $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations.

The LSND experiment uses neutrinos from $\pi$ and $\mu$ decay from the beam stop of the Los Alamos Meson Physics Facility (LAMPF).

i) $\pi^+ \rightarrow \mu^+\nu_\mu$ (in flight or at rest); ii) $\mu^+ \rightarrow e^+\bar{\nu}_e\nu_\mu$ (at rest); iii) $\pi^- \rightarrow \mu^-\bar{\nu}_\mu$ (in flight); iv) $\mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$ (at rest). The relative yield of $\bar{\nu}_e$ above an energy of 36 MeV is only $\sim 4 \times 10^{-4}$.

LSND consists of a tank containing 167 tons of liquid scintillator (doped mineral oil, CH$_2$). It detects $\bar{\nu}_e$ by the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ which gives a prompt $e^+$ signal followed by a delayed 2.2 MeV $\gamma$-ray from the capture reaction $np \rightarrow d\gamma$. 
This experiment has reported the observation of 22 events with $e^-$ energy between 36 and 60 MeV and only $4.6 \pm 0.6$ background events. The probability that this excess results from a statistical fluctuation of the background is $4.1 \times 10^{-8}$. If attributed to $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations, it corresponds to an oscillation probability of $(0.31 \pm 0.10 \pm 0.005) \times 10^{-2}$, averaged over the neutrino energy spectrum and spatial distribution. Figure 1 shows the favoured regions of the oscillation parameter plane, together with the regions excluded by other experiments.

The KARMEN experiment

The Karlsruhe-Rutherford Medium Energy Neutrino (KARMEN) experiment is being performed at the spallation facility ISIS at the Rutherford-Appleton Laboratory. An important difference with respect to LAMPF is that the ISIS beam is pulsed with a time structure consisting of two 100 ns long pulses separated by 320 ns (this sequence has a repetition rate of 50 Hz). Thus it is possible to separate neutrinos from muon and pion decay from their different time distributions with respect to the beam pulse.

The KARMEN experiment has observed no signal above the expected background providing no evidence for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations. The boundary of the region in the oscillation parameter plane excluded by this result lies approximately in the middle of the region favoured by LSND, hence there is no disagreement between the two experiments. The KARMEN experiment is being upgraded to increase its sensitivity to $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations. Within two years, it should either confirm or disprove the LSND result.

The CERN experimental programme on neutrino oscillations

Two experiments, CHORUS and NOMAD, are presently taking data in the wide-band neutrino beam from the 450 GeV SPS with the aim of detecting $\nu_\mu - \nu_\tau$ oscillations.

The method adopted by both experiments consists in detecting $\tau^-$ production with a sensitivity corresponding to a $\nu_\tau/\nu_\mu$ ratio of $\sim 2 \times 10^{-4}$.

CHORUS aims at detecting the characteristic decay of the short-lived $\tau$ lepton in nuclear emulsion. It started data taking in May 1994. At the end of October 1995 the emulsion target was removed and developed (the measuring capability amounts to $\sim 200,000$ events/year). New emulsion stacks are presently exposed to the neutrino beam for an additional two-year run.

NOMAD aims at identifying $\tau^-$ production and decay using only kinematical criteria.

Data have been recorded since May 1995 with a reduced target mass; data taking in parallel with CHORUS is scheduled until the end of 1997.

The NOMAD experiment aims at detecting $\tau^-$ production by observing both leptonic and hadronic decay modes of the $\tau^-$. 

Recently, both CHORUS and NOMAD have presented preliminary results on $\nu_\mu - \nu_\tau$ available
oscillations based on a small fraction of the data, which exclude \( \nu_\mu - \nu_\tau \) oscillations with mixing angle \( \sin^2 2\theta > 0.005 \) for large \( \Delta m^2 \). NOMAD has also presented the results from a search for \( \nu_\mu - \nu_e \) oscillations which excludes the \( \Delta m^2 > 10\text{eV}^2 \) region of oscillation parameters suggested by LSND.

The COSMOS experiment at Fermilab

This experiment uses the neutrino beam which will become available at Fermilab near the end of the century when the new Main Injector (MI) will start operation.

The COSMOS experiment is conceptually similar to CHORUS. Table 9.3.2 compares the main parameters of the future Fermilab Main Injector and neutrino beam with those presently available from the CERN SPS. It must be pointed out that the cross-section for \( \tau^- \) production from \( \nu_e \)'s in the neutrino beam from the Fermilab Main Injector is a factor of \( \sim 5 \) lower than in the CERN beam because of the lower energy of the interacting neutrinos.

COSMOS will start data taking around the year 2000. Figure 2 shows the region of the \( \sin^2 2\theta, \Delta m^2 \) plane which will be excluded by COSMOS if no oscillation signal is observed, together with the anticipated combined CHORUS and NOMAD limit.

9.3.3 Long base-line experiments at accelerators

If the atmospheric neutrino problem is the result of \( \nu_\mu - \nu_\tau \) oscillations, then the value of \( \Delta m^2 \approx 10^{-2}\text{eV}^2 \) needed to explain the data will give rise to oscillations which can be detected by installing a suitable detector at a distance of the order of 1000 km from a source of neutrinos with energies of the order of 10 GeV.

The first long baseline accelerator experiment to address this problem will use a wide-band neutrino beam from the KEK 12 GeV proton synchrotron in conjunction with the Super-Kamiokande detector at a distance of 250 km. Both \( \nu_\mu \) disappearance and \( \nu_e \) appearance will be studied. This experiment should start data taking at the beginning of 1999.

Figure 9.2: Region of the \( \sin^2 2\theta, \Delta m^2 \) plane excluded by COSMOS after a four-year run if no \( \nu_e \) signal is observed. Also shown is the anticipated limit from CHORUS and NOMAD, together with limits from previous experiments.

The future neutrino programme at Fermilab includes a long base-line experiment. The neutrino beam from the Main Injector is directed towards the Soudan underground laboratory in Minnesota at a distance of 730 km from Fermilab.

The Soudan laboratory will be equipped with a new underground hall oriented along the neutrino beam where the Main Injector Neutrino Oscillation Search (MINOS) will be installed.

The MINOS detector consists of magnetised iron plates interleaved with active detector planes providing at the same time calorimetric and tracking information. The total mass of the MINOS detector is 10,000 tons. With such a mass and a wide-band beam, one expects approximately 20,000 \( \nu_\mu \) CC events per year.

The MINOS detector is used in conjunction with a second detector of similar conceptual design but with a much smaller mass located at a distance of \( \sim 1 \text{ km} \) from the proton target.

MINOS will begin data taking at the beginning of the next century in parallel with the short base-line COSMOS experiment described previously. It will be able to demonstrate the
<table>
<thead>
<tr>
<th></th>
<th>CERN SPS</th>
<th>Fermilab MI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons energy</td>
<td>450 GeV</td>
<td>120 GeV</td>
</tr>
<tr>
<td>Protons on target/cycle</td>
<td>$2 \times 10^{13}$</td>
<td>$6 \times 10^{13}$</td>
</tr>
<tr>
<td>Cycle time</td>
<td>14.4s</td>
<td>1.9s</td>
</tr>
<tr>
<td>Protons on target/year</td>
<td>$1.2 \times 10^{19}$</td>
<td>$3 \times 10^{20}$</td>
</tr>
<tr>
<td>Average energy of interacting $\nu_\mu$</td>
<td>40 GeV</td>
<td>16 GeV</td>
</tr>
</tbody>
</table>

Table 9.1: List of relevant parameters for the present CERN neutrino beam and for the anticipated beam from the Fermilab Main Injector (MI).

Another possibility for long base-line neutrino oscillation searches, which has been recently proposed consists in aiming a neutrino beam from the CERN SPS to Gran Sasso National Laboratory in Italy at a distance of 732 km. The three existing underground halls at Gran Sasso, under ~ 4000 m of water equivalent, are already oriented towards CERN and ICARUS, a 600 tons detector suitable for oscillation searches, will start operation in 1999 with the main goals of searching for proton decay and of studying atmospheric and solar neutrinos.

ICARUS is a new detector concept based on a liquid Argon Time Projection Chamber (TPC) which allows three-dimensional reconstruction of events with spatial resolution of the order of 1 mm.

9.4 Neutrino Experiments at Reactors

9.4.1 Introduction

After 1970 the main motivation for reactor neutrino experiments was to look for physics beyond the standard model: neutrino oscillation, neutrino mass and neutrino magnetic moment. The search for $\nu$ oscillation or $\nu$ decay is related to neutrino mass. Neutrino magnetic moment can explain also solar $\nu$ deficit. Stringent limits on $\nu$ decay have been obtained and there is no more experimental activity in that field near reactors.

9.4.2 Reactors as Neutrino source

Neutrinos are produced by $\beta$ decay in fission fragments, so the energy of the neutrinos is below 10 Mev. A good knowledge of the reactor parameters is needed to obtain the neutrino flux emitted by a reactor. The energy spectrum and the flux of the $\nu$ produced by a reactor have been carefully measured above 2 Mev using detectors close to the reactor core. In the inverse $\beta$ decay reaction on proton (threshold 1.8 Mev): $\bar{\nu}_e + p \rightarrow e^+ + n$ the neutrino energy is deduced from the $e^+$ energy. The experimental accuracy on the neutrino flux is 1.4% to be compared with 2.7% on the expected flux.

Below 2 Mev the $\bar{\nu}_e$ spectrum can only be calculated. Uncertainties from the contribution of the neutron capture in fission fragments have been calculated recently. This is important for experiments searching for neutrino magnetic moment effect in neutrino electron elastic scattering.

Many sites have been used around the world, but few are still in operation for neutrino studies. Laboratories which are close to the reactor core are now used to measure very low cross section processes (neutrino electron or neutrino deuteron scattering). In these experiments the value of the $\nu$ flux (reactor power) is more important than the overburden. The search for $\nu$ oscillation imposes now long baseline experiments: the overburden and the reactor power are significant. Comparisons between available sites are shown in table 9.2.
9.4.3 Status of deuteron experiments

The main goal of these experiments is the measurement of the cross section of the Neutral Current on Deuteron (single neutron in the final state): $\bar{\nu}_e + d \rightarrow \bar{\nu}_e + p + n$. In addition the Charged Current reaction on the Deuteron (two neutrons in the final state) can be measured: $\bar{\nu}_e + d \rightarrow e^+ + n + n$.

The knowledge of these cross sections is a unique probe of the axial-vector contribution to the neutral current. The accuracy of these experiments has been limited to 15% due to the single neutron background induced by cosmic ray muons.

In the UCI experiment installed at the Bugey site the single neutron background is low (60 neutrons per day) while the expected $\nu$ rate is 35 per day. An accuracy of 5% (equivalent to the theoretical expectation) will be obtained in 1997. It can be seen that the neutron background induced by cosmic rays can be eliminated by an appropriate shielding. This is encouraging for future low background experiments near reactors.

Another experiment is running at Krasnoyarsk at a larger distance (34 m.) The background is large (220 neutrons per day) and the expected rate lower (15 per day). They will obtain an accuracy of 10% within few years.

9.4.4 Neutrino Oscillation Search

The only channel which can be studied in a reactor experiment is the disappearance of $\bar{\nu}_e$. The signature of the $\bar{\nu}_e$ interaction is the inverse $\beta$ decay. CC reaction is forbidden for other neutrinos ($\nu_\mu, \nu_\tau$) at the energies of reactor neutrinos. As a consequence the sensitivity in mixing is limited to few % but the $\delta m^2$ sensitivity can be extended up to $10^{-3}eV^2$.

During the last 15 years many experiments have been conducted to search for neutrino oscillation at distances ranging from 8m to 70m. No disappearance effect have been observed. From these experiments the limits on oscillation parameters are listed in table 9.3.

To extend the sensitivity in $\delta m^2$ to $10^{-2}eV^2$ detectors have to be located at a distance as large as 1km. The domain covered will allow to probe the $\nu_e - \nu_\mu$ transition to solve the atmospheric neutrino anomaly.

The challenge is to compensate the neutrino flux reduction ($10^{-1}$) by reducing the cosmic ray induced background in the detector. Two experiments have proposed two different concepts to reduce the background:

- The CHOOZ experiment is located underground (300 mwe). The detector is made of a target containing 5.6 m$^3$ of Gadolinium loaded liquid scintillator. The 8 Mev $\gamma$ from Gd de-excitator give a clean signature of the neutron capture, above the maximum energy of the natural radioactivity (2.6 MeV from Thallium). The target is surrounded by 145 m$^3$ of unloaded scintillator. This scintillator blanket provides an additional reduction of neutron background by tagging muons going through the side of the detector and absorbing those neutrons produced in the rocks surrounding the detector. The experiment is taking data since august 1996. Preliminary results will be available in 1997.
- The Palo Verde experiment makes use of a segmented liquid scintillator detector being
installed in an underground vault with a relatively small overburden of 46mwe. To reduce the cosmic ray induced neutron background, the discrimination between recoil protons and positron is made by requiring a triple coincidence between target cells as a signature of the positron and the two 511-Kev $\gamma$ rays from the positron annihilation. The sensitive volume is made of 66 cells, 9m long, containing Gd loaded liquid scintillator. This volume is surrounded by a one-meter-thick water buffer. Around the water buffer is installed an active muon system. The experiment will start taking data in the second half of 1997.

The next logical step will be to implement an experiment at a distance larger than 10km in order to search for $\nu$ oscillation down to $10^{-4}eV^2$. The interest of such a search should be studied on the basis of the results of the ongoing experiments (reactor, atmospheric $\nu$, solar $\nu$).

To get a neutrino event rate of 10 events per day the target size is of the order of 1 Kton. The IMB site, 13 km away from the 3600 Mtth Perry reactor, is a good candidate with an overburden of 1570-mwe. Another site is studied in Japan 60 km away from a reactor.

Research and development are needed on scintillators (light transmission, stability, radio-purity) before to be able to run a 1Kton detector. Other field of physics will be accessible with such a detector: proton decay, supernova, solar neutrino. The experience from the large underground detector in preparation like Borexino will be useful in that study.

9.4.5 Neutrino-electron scattering

Reactors are well suited to study $\bar{\nu}_e e^- \rightarrow \nu_e e^-$ scattering. Both charged (CC) and neutral weak currents (NC) are involved. They are expected to interfere if the NC and CC final state neutrinos are identical, as assumed in the Standard Model. A measurement of the differential cross section allows, in principle, to determine the Weinberg angle $\sin^2 \theta_W$ and to observe the interference which is expected to be destructive for reasonable values of $\sin^2 \theta_W$. Practically however $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ only has a good sensitivity to both effects, while $\nu_e e^- \rightarrow \nu_e e^-$ essentially probes the interference.

In addition, provided their magnetic moments are non vanishing, neutrinos will have electromagnetic interactions, making them scatter from a left handed active state, from the point of view of weak interaction, into a sterile right handed state. The cross-section is proportional to the effective magnetic moment

$$\mu_\nu = \sqrt{\sum_{\ell} |\mu_{\ell\ell}|^2}, \quad (\ell = e, \mu, \tau \ldots)$$

with $\mu_{\ell\ell'}$ the neutrino magnetic moment matrix. This matrix can either be Dirac like, in which case both static ($\ell = \ell'$) and transition ($\ell \neq \ell'$) moments may be non-zero, or Majorana like, in which case the transition moments only may be finite, the static moments being exactly zero.

If large enough, the magnetic moment will affect the cross-section for all neutrino interactions, and cause neutrinos to precess in magnetic fields. In fact, neutrino magnetic moments of order $10^{-11} - 10^{-10}$ have been invoked as an alternative explanation to neutrino oscillations for the observed solar neutrino deficit. On the other hand, data on stellar cooling and supernova collapse, analysed in the frame of appropriate stellar models, give stringent upper limits.

Beam dumps at intermediate energy accelerators produce $\nu_e$ with energies from 0 to 50 MeV. A measurements of $\nu_e e^- \rightarrow \nu_e e^-$ scattering has
been performed at the LAMPF beam dump. In spite of a limited statistics the experiment showed that there was no room for a constructive interference, and confirmed the destructive interference. As expected the experiment did not give a precise value for the Weinberg angle. It produced however an upper limit for the magnetic moment of the $\nu_e$: $\mu_\nu < 1.08 \cdot 10^{-9}$.

Reactors produce $\bar{\nu}_e$ with lower energies, ranging from 0 to 8 MeV. The UC Irvine group led by F. Reines built the first detector dedicated to the study of $\bar{\nu}_e$ scattering. It was operated successfully at the Savannah River Plant (SRP), observing the process for the first time. Vogel and Engel, using the presently best determination of the reactor spectrum and fixing $\sin^2 \theta_W$ to the presently accepted value, find that the measured rate is larger than the expected one. Taken literally this discrepancy points to a neutrino magnetic moment $\mu_\nu = (2 - 4) \cdot 10^{-10}$.

More recently, a group from the Kurchatov Institute in Moscow has also successfully observed $\bar{\nu}_e e^-$ scattering. The measured rate is compatible with expectations, obtained with $\sin \theta_W = 0.23$, and leads to the limit $\mu_\nu < 2.4 \cdot 10^{-10} \mu_B$ for the neutrino magnetic moment.

It clearly appears important to improve by a large factor on these results, and clarify the situation. For these reason the MUNU collaboration has built a new detector. It is being installed at Bugey. The central component is a 1 m$^3$ CF$_4$ time projection chamber (TPC) operated at 5 bar, which serves as active target. With its imaging capability the detector should provide a clear signature for good events. Some 10 events per day are expected, with a threshold on the electron kinetic energy of 500 keV. The background can be determined from the observed rate of backward electrons. To reduce the background the detector is surrounded by a liquid scintillator veto and anti-Compton detector, and by various shielding layers. In addition it is made with radiochemically very clean materials. Thanks to the low threshold, the experiment should be sensitive to magnetic moments of order $2 - 3 \cdot 10^{-11} \mu_B$, a factor 10 better than in previous experiments.

In principle, it is also possible to measure the neutrino magnetic moment by studying neutrino-nucleus scattering at low energy. The cross-section is enhanced by a factor $Z^2$ because of coherence. The recoil energy of the nucleus is however very small, and difficult to detect with standard techniques. Cryogenic detectors, which are presently being developed and used, for instance to search for double beta decay or dark matter, do have the required sensitivity. Simultaneous measurement of the phonons and the ionisation allows to distinguish nuclear recoil from electron-recoil, leading to a major background suppression. This may make this scheme attractive.

Instead of nuclear reactors, one may consider using electron capture radioactive sources. Both the GALLEX and the SAGE collaborations have calibrated their solar neutrino detectors with $^{51}$Cr sources. The GALLEX source had an activity of 61.9 $\pm$ 1.2 PBq at the end of irradiation. There are two advantages in using a source: the neutrinos have well defined energies, and it is possible to approach the source very closely. Large detector masses are nevertheless required to study neutrino-electron scattering.

9.5 Solar Neutrinos

9.5.1 The solar neutrino problem

The solar neutrino problem had origin from the discrepancy between the expectations of the solar $\nu_e$ flux, as calculated by the Solar Standard Model, and the experimental results.

But even if we forget the Solar Model and we study the compatibility among the available experimental data we find an internal inconsistency. In Table 9.4 the experimental results are quoted; they constraint in different ways the neutrino fluxes from the various sources. A fourth equation can be written taking into account the constraints introduced by the solar luminosity.

The Kamiokande results, due to its high threshold, constraint only the neutrino flux from$^8$B. Homestake and Gallium experiments involve also lower energy neutrino fluxes.
Table 9.4:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measured flux S.M. expectation</th>
<th>Threshold (MeV)</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>0.27±0.06</td>
<td>0.814</td>
<td>( S_c = \Sigma \sigma L_c \phi_i )</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>0.44±0.06</td>
<td>7.5</td>
<td>( S_k = \sigma_\beta \phi(B) )</td>
</tr>
<tr>
<td>Gallium (Gallex, Sage)</td>
<td>0.5 ± 0.06</td>
<td>0.235</td>
<td>( S_q = \Sigma \sigma_\nu \phi_i )</td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td>( K = \Sigma (Q/2+ &lt; E &gt; \gamma_i) Q_i )</td>
</tr>
</tbody>
</table>

If we try to extract the \(^7\text{Be}\) neutrino flux from the four equations of Table 9.4 we obtain a flux negative or very close to zero. In any case the \(\nu\) flux from \(^7\text{Be}\) appears to be smaller than the \(^8\text{B}\) flux. This is in strong contradiction with the sequence of the nuclear reactions within the Sun, where the reaction involving \(^7\text{Be}\) precedes the reaction involving \(^8\text{B}\) and thus the \(^7\text{Be}\) nuclides are in some ways the father than \(^8\text{B}\). This is the paradox of the present situation of the Solar neutrino problem.

9.5.2 New neutrino physics?

To solve this paradox the hypothesis of new neutrino physics has been raised, and in particular the hypothesis of neutrino oscillation has been taken into consideration. The oscillation can take place in the travel between Sun and Earth (Vacuum Oscillations) or within the Solar Matter (Oscillation in matter: MSW effect).

In the frame of the assumption of only two-neutrino mixing, in the plane \(\Delta m^2 \text{ vs } \sin^2 \theta\), the main parameters of the oscillations, two regions are still allowed for MSW by the present experimental results: one at Small Mixing Angle (SMA) and the second one at Large Mixing Angle (LMA). These two zones are 90% C.L. regions around two points, which represent the Best Fit Values. A third zone exists, at 99% C.L. at low \(\Delta m^2\) and large mixing angle.

Similarly for the Vacuum Oscillation a large region is still allowed, around a Best Fit value.

For both the oscillations: Vacuum Oscillation and MSW the \(^7\text{Be}\) region is crucial. For the oscillations in matter in the SMA region the \(^7\text{Be}\) neutrino flux is much more reduced than the \(^8\text{B}\) flux. This is true also in the LMA, even if the effect is not so strong.

For the oscillation in vacuum the modulation wavelength is very short in the \(pp\) neutrino region, with the consequence that the effect appears to be averaged. In the high energy range of the solar neutrino spectrum the wavelength is larger than the distance Sun-Earth and the effect cannot be detected. Finally at the \(^7\text{Be}\) neutrino energy, the Sun-Earth distance is just few times the wavelength \([L_{\text{Sun-Earth}} = (n+1/2)\lambda]\).

Evidence of the neutrino oscillation can be obtained:

1. by comparing the total neutrino fluxes with what expected by the Solar Model;
2. by studying the energy spectra for non monochromatic sources;
3. by looking for seasonal variations which have to be different from what expected by the pure geometrical effect (eccentricity of the Earth orbit), as a consequence of the Vacuum Oscillations. Another important effect is the possible day/night flux difference due to the MSW effect due to the possibility that \(\nu_\mu\) should be converted again to \(\nu_e\) crossing the Earth;
4. by detecting neutral current events which can be induced by any flavour neutrinos.

9.5.3 Future experiments

In Table 9.5 the main characteristics of the future experiments are listed

All these experiments have big problems for the background. Borexino has carried out the
experiment C.T.F. (Counting Test Facility) just to demonstrate the feasibility of the experiment for what concerns the radiopurity of the detecting materials.

SNO and Borexino are surely in condition to give a very good contribution to the clarification of the problem of the solar neutrino oscillations, the first for what concerns the study of the neutral currents, the second one for the analysis of the $^7$Be flux and its time variation. To be more specific we discuss what it can be expected from the experiments in the next few years in terms of flux, energy spectrum, time variations.

In term of flux if for instance we assume the SMA as correct, SNO and Borexino are able to rule out completely the LMA and Borexino also the V.O. region. If the V.O. hypothesis is assumed correct, SNO and Borexino can rule out the SMA.

The study of the energy spectrum in the $^8$B region at an energy higher than 5 MeV (Superkamiokande, SNO) could disentangle the possible contribution from the oscillations but this analysis is hard in the case of the elastic scattering, where the differences are only few percent.

The seasonal variation can be well studied by Borexino, because the $^7$Be neutrino is monoenergetic; all the $\Delta m^2$ vs $\sin^2 2\theta$ plane can be explored.

Finally both the $^6$B and the $^7$Be fluxes can give origin to the day/night effect; its detection could be easier in the $^6$B region.

Three further experiments have to be mentioned GNO, Hellaz and Supermumu.

GNO (Gallium Neutrino Observatory) is just a prolongation of Gallex with increased volume and an upgrading of the analysis devices (proportional counters). In this way the Gallex collaboration planes to depress both the statistical and the systematical errors.

Two new experiments, still in R&D phase, are Supermumu and Hellaz. Both are based on gas TPC’s. Hellaz planes to use a 2000 m$^3$ TPC filled with He-CH$_4$ at 5-10 bars, cooled at 77 K. The resolution in angle and in energy should be very good ($\sigma_\theta \sim 35$ mrad and $\sigma(E_\nu)/E_\nu \sim 2 - 4\%$). The energy threshold should be $\sim$ 100 KeV.

Supermumu is similar to Hellaz, but it should employ CF$_4$.

We can conclude that there is a good chance that the solar neutrino problem should be solved in the first years of the 21st century.

Experiments on $^7$Be neutrinos, on neutral current events and on time variations could be decisive in this field.

### Table 9.5:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reaction</th>
<th>Experimental method</th>
<th>Threshold (MeV)</th>
<th>Expected start-up</th>
<th>Statistics [full SSM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superkamiokande</td>
<td>$\nu_e e^- \rightarrow \nu_e e^-$</td>
<td>Č events</td>
<td>5.</td>
<td>already running</td>
<td>65/d</td>
</tr>
<tr>
<td>SNO</td>
<td>$\nu_e d \rightarrow p\nu e^-$</td>
<td>Č events</td>
<td>5.</td>
<td>1997</td>
<td>20/d</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19997</td>
<td>7/d</td>
</tr>
<tr>
<td>Borexino</td>
<td>$\nu_\beta e^- \rightarrow \nu_\beta e^-$</td>
<td>liquid scint.</td>
<td>0.25</td>
<td>1999</td>
<td>50/d</td>
</tr>
<tr>
<td>ICARUS</td>
<td>$\nu_e e^- \rightarrow \nu_e e^-$</td>
<td>liquid Ar</td>
<td>5.</td>
<td>1999</td>
<td>0.8/d</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2/d</td>
</tr>
</tbody>
</table>

#### 9.6 Atmospheric neutrinos

#### 9.6.1 Introduction

Atmospheric neutrinos are produced in the cascade originated in the atmosphere by a primary cosmic ray. This field has a special interest because the water Čerenkov experiments, IMB in the United States and Kamiokande in Japan, discovered that the ratio between events with
a muon and those with an electron was lower than expected. A possible interpretation of this anomaly is the oscillation of the neutrino species in the path length between the production point and the detector (in the range 10 - 13000 km). The anomaly was not confirmed by the proton decay iron fine-grained experiments NUSEX and Frejus.

9.6.2 The atmospheric neutrino beam

Atmospheric neutrinos are produced in the pion and muon decays (kaons are important only at high energies). From these decay channels one expects at low energies about twice muon neutrinos with respect to electron neutrinos. This result doesn’t change very much with a detailed calculation.

There are several different calculations on the atmospheric neutrino flux. In order to compare them, we can separate the low-energy region (less than 1 GeV) from the high-energy region (more than 1 GeV). This separation corresponds to different event topologies in the detector. The low-energy region generally corresponds to events with the interaction vertex inside the detector and fully contained (peak neutrino energy around 1 GeV); the high-energy region, to events either with the interaction vertex inside the detector but not fully contained (peak neutrino energy around a few GeV) or with the interaction vertex in the rock outside the detector (peak neutrino energy around 100 GeV); and in the latter case only muon neutrinos can be detected. A comparison of different calculations of the atmospheric neutrino flux in the low-energy region has been made by Barr, Gaisser, Stanev (BGS). The current estimate on the error of the ratio \( \nu_e/\nu_\mu \) is ±5%. An important check for this kind of calculation comes from comparison with high-altitude muons.

Several calculations also exist for the high-energy region, where the contribution due to kaon decay (50% in the energy interval between 10 GeV and 1000 GeV) is important. In the region of \( 10 < E_\nu < 1000 \) GeV, the uncertainty in the muon neutrino flux is 14%.

9.6.3 Internally produced events

The events due to neutrino interactions inside the detector can be fully contained: the secondary particles are contained inside the fiducial volume of the detector and a good discrimination between events with muons and those with electrons is possible. In the case of Kamiokande, Superkamiokande, IMB and Soudan2, the Table 9.6 lists only the events satisfying the definition of quasi elastic. This means single-ring events in the case of the water Čerenkov detector. The shape of the ring is a signature for a muon or an electron.

The main results from the inspection of Table 9.6 are:

1) The water Čerenkov experiments measure a significant deficit of muon neutrinos compared to electron neutrinos. Since the error in the prediction of R is small (5%), this result is statistically significant. Because the absolute flux of electron neutrinos is in rough agreement with the predictions (assuming the BGS flux calculation), the preferred hypothesis is that the deficit is due to \( \nu_\mu \rightarrow \nu_\tau \) oscillations (and not to \( \nu_\mu \rightarrow \nu_e \)). The preferred values of the oscillation parameters are: \( \delta m^2 \) of the order of 0.01eV\(^2\) and \( \sin^2(\theta) \) near 1. Preliminary results (April 1997) of the Superkamiokande experiment are in agreement with the past measurement.

2) This effect is not seen in the fine grained calorimeters Frejus and NUSEX. Even if the errors are large they are in apparent contradiction to the water Čerenkov events. The Soudan2 detector gives intermediate results.

The most remarkable feature of the Kamiokande partially contained (or multi GeV) data is the dependence of the flavour ratio on the measured zenith angle (related to the direction of the incident neutrinos). This angular dependence agrees with a model in which the path length of the downward \( \nu_\mu \) is too short to oscillate and the upward \( \nu_\mu \), travelling for a much longer distance, are attenuated by oscillations.
9.6.4 Externally produced events

External events are produced by neutrino interaction in the rock around the detector so the effective target is larger. The detector sensitivity depends on the surface and not on the active mass. Two kinds of events can be detected:

a) Stopping muons: low energy muons produced from neutrino interaction in the rock and stopping inside the detector. In the interpretation of the data there are problems connected with the low energy neutrino cross-section and with a possible background due to large angle pions produced from the cosmic ray muons.

b) Through-going muons: upward-going muons produced from neutrino interactions in the rock below the apparatus and crossing the entire apparatus. If the oscillation hypothesis is true and with the value suggested by internal events, it should be possible to see a clear signature in the angular distribution of the up-going muons. In fact vertical neutrinos (having a path length of the order of 13000 Km) should be attenuated (a factor 2 for maximum mixing) while horizontal neutrinos (having a shorter path length) should not be attenuated. Data on up-going through-going muons come from Kamiokande, Superkamiokande (April 1997), IMB, Baksan and MACRO.

The Baksan detector, located in the Baksan underground laboratory in Russia at a minimum depth of 850 h\(g/cm^2\), consists of 3150 liquid scintillator counters. MACRO consists of liquid scintillators and streamer-tube chambers. It is located in the Gran Sasso underground laboratory.

The neutrino induced upward-going muons must be separated from a huge background due to down-going muons. The selection is based on the directionality of the Čerenkov light or on the time of flight measurement (Baksan, MACRO). Table 9.7 summarises the available statistics. The angular distribution of the data is at the moment not conclusive for the presence of oscillations.

9.6.5 Future

It is clear that we have an experimental problem for both categories of events. The question is whether it can be solved in the future. It is not only a problem of statistics but also of systematics connected with the quality of detectors. The detectors that currently are taking data are:

1) Internal events: SOUDAN2, MACRO, Superkamiokande. Superkamiokande began operation in April 1996. The Multi-GeV events are now contained (due to the dimensions) and the quality of the data is improved because of the larger PM coverage. Starting in 1999, it is planned to take data with a long base line (250 km) 1.4 GeV \(\nu_\mu\) beam with a 1000-ton water Čerenkov near detector. This detector can be used at the beginning to check the systematic error of the far detector for atmospheric neutrinos. After 2-3 years of running with the long base line neutrino beam (around 2002-2003), Superkamiokande should

<table>
<thead>
<tr>
<th>Experiment (contained events)</th>
<th>(R = \frac{(\mu/e)<em>{\text{data}}}{(\mu/e)</em>{\text{MC}}})</th>
<th>Exposure (Kton year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamiokande</td>
<td>0.61 ±0.07_{\text{stat}} ± 0.05_{\text{syst}}</td>
<td>7.7</td>
</tr>
<tr>
<td>SuperKamiokande 1997</td>
<td>0.64±0.04±0.06</td>
<td>12.8</td>
</tr>
<tr>
<td>IMB</td>
<td>0.55 ± 0.05±0.12</td>
<td>7.7</td>
</tr>
<tr>
<td>Frejus 1995</td>
<td>1.0±0.15±0.08</td>
<td>2.0</td>
</tr>
<tr>
<td>Soudan2 1996</td>
<td>0.75±0.16±0.10</td>
<td>1.5</td>
</tr>
<tr>
<td>Nusex</td>
<td>0.99±0.29±?</td>
<td>0.74</td>
</tr>
<tr>
<td>partially contained events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kamiokande (MultiGeV)</td>
<td>0.59±0.08</td>
<td>8.2</td>
</tr>
<tr>
<td>Frejus 1995</td>
<td>0.99±0.13±0.08</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 9.6: Internally produced events (contained and partially contained)
<table>
<thead>
<tr>
<th>data</th>
<th>IMB</th>
<th>Kamiokande</th>
<th>SuperKamiokande</th>
<th>Baksan</th>
<th>MACRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>617</td>
<td>364</td>
<td>267</td>
<td>558</td>
<td>351</td>
</tr>
<tr>
<td>prediction</td>
<td>0.93</td>
<td>0.91</td>
<td>0.88±0.05_{stat}</td>
<td>1.0±0.04_{stat}</td>
<td>0.74±0.04_{stat}</td>
</tr>
<tr>
<td>±0.04_{stat}</td>
<td>±0.05_{stat}</td>
<td>±0.08_{syst}</td>
<td>±0.06_{syst}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9.7: Upward-going muons data. The prediction is based on the Bartol neutrino flux. The theoretical uncertainty (17%) is not included in the errors.

First, it provides a unique way to look for neutrino masses of the Majorana type. With such masses neutrinoless double beta decay \((\beta\beta0\nu) (A, Z) \rightarrow (A, Z + 2) + e^- + e^-\) can occur. It violates lepton number conservation by two units. The half life is directly related to the effective neutrino mass:

\[
\langle m_\nu \rangle = \sum_{j=1}^{2N} \epsilon_j m_j U_{e_j}^2, \text{ with } [T_{1/2}^{0\nu}] \propto \langle m_\nu \rangle^{-2}.
\]

Here \(m_j\) are the eigenmasses, \(N\) the number of flavours, \(\epsilon_j\) the corresponding CP eigenvalues (±1), and \(U_{e_j}\) the mixings of the mass eigenstates to the electron neutrino. The two electrons carry away all of the kinetic energy \(E_0\) released in the decay.

Second, the study of double beta decay gives insight on the coupling of the neutrino to hypothetical light neutral bosons, generically named Majorons \((\chi^0)\). Such Majorons could be emitted in the \((A, Z) \rightarrow (A, Z + 2) + e^- + e^- + \chi^0\) double beta decay \((\beta\beta0\chi)\). The sum energy spectrum of the two electrons extends from 0 to \(E_0\), as the Majoron carries away a fraction of the energy. Many models with Majorons have been built, including some in which two Majorons are emitted. In the oldest scheme the spectral shape is quite hard peaking at \(2/3 E_0\). The half life depends on \(\langle g_{eff} \rangle\), the effective coupling constant of the Majoron to the neutrino:

\[
[T_{1/2}^{\chi^0}] \propto \langle g_{eff} \rangle^{-2}.
\]

For the sake of comparison, experimentalists usually interpret their results in terms of this model.

The study of the allowed double beta decay \((\beta\beta2\nu) (A, Z) \rightarrow (A, Z + 2) + e^- + e^- + \bar{\nu}_e + \nu_e\) does not address fundamental questions. It

check directly with disappearance experiments the oscillation pattern resulting from the current water Čerenkov atmospheric neutrino data.

2) External events: currently are taking data SuperKamiokande, Baksan, MACRO. There are four new detectors under construction that could give information on the atmospheric neutrino problem: Icarus, Nestor, Baikal, Amanda.

Icarus will be very interesting for neutrino internal events. The mass will not be competitive with SuperKamiokande, but the event pattern will be much cleaner.

Nestor is an underwater Čerenkov detector, to be located in the Mediterranean sea, near Pilos in Greece. The first stage of the project will consist of a tower having a nominal area of about 2000 m\(^2\) for E>5 GeV and 20000 m\(^2\) for E>1 TeV. The collaboration has chosen to maximise the surface for high-energy muons, so it will not be competitive with SuperKamiokande for internal events, but should be interesting for external events.

Baikal is an underwater Čerenkov detector in the Baikal lake at a depth of 1300 m. The final detector should have an effective area of 2300 m\(^2\) for E\(_\mu\) > 1 TeV.

Amanda is an under-ice Čerenkov detector, to be located near the US South Pole base. The final area is expected to be similar to that of Nestor. For atmospheric neutrinos, the same consideration as those for Nestor.

### 9.7 Double beta decay

The study of nuclear double beta decay sheds light on physics beyond the standard model.
is nevertheless interesting in the sense that it probes the nuclear models with which the nuclear matrix elements for all the decay modes are calculated. The corresponding elements must be known in order to interpret the measured half lives on $\beta\beta^{0}\nu$ and $\beta\beta^{0}$ decay in terms of neutrino masses and Majoron coupling. In $\beta\beta^{2}\nu$ decay the spectrum of the sum energy of the two electrons ranges from 0 to $E_{0}$, and peaks at roughly $1/3\ E_{0}$.

### 9.7.1 Recent results

There are three ways to look for double beta decay:

1) direct searches, in which one looks with a detector for the two electrons emitted by a source. The energy of the electrons is measured, so that the three decay modes can be distinguished.

2) geochemical experiments, in which one searches, in an ore containing double beta decay candidates, for an abnormal isotopic abundance of the daughter nuclei. The three modes cannot be distinguished.

3) radiochemical experiments, similar to the geochemical ones, but in which the daughter nuclei are unstable, and can be identified by their decay.

We shall here focus on direct searches. Experiments have become more and more sensitive over the years, with larger target masses. Much progress has been achieved in selecting radiochemically clean components for the construction of detectors, leading to a substantial reduction of the background from natural activities. To minimise the background from direct cosmic hits, or from cosmogenic activations, detectors are usually operated in underground laboratories. Calorimeters with superior energy resolution are particularly well suited for the search of the $\beta\beta^{0}\nu$ decay peak. Tracking devices are also used. In these good event candidates can be selected from their topology, which leads to a further background reduction.

Presently $\beta\beta^{2}\nu$ decay has been observed in several nuclei ($^{48}\text{Ca}, \quad ^{76}\text{Ge}, \quad ^{82}\text{Se}, \quad ^{100}\text{Mo}, \quad ^{128}\text{Te}, \quad ^{130}\text{Te}, \quad ^{150}\text{Nd}$). At the same time the limits on the other modes keep getting more constraining. We shall here mention only the most recent developments.

$^{76}\text{Ge}$. This nucleus has been studied for several years, since Ge detectors with large mass can be operated as calorimeters with excellent energy resolution. Presently the best results are those obtained by the Heidelberg-Moscow collaboration, which operates an array of 5 crystals made from Ge enriched to 86-88 % in $^{76}\text{Ge}$, with a total mass of 11 kg, in the Gran Sasso underground lab.

Data corresponding to 15 kg-yr have been accumulated so far. $\beta\beta^{2}\nu$ was clearly observed, with a half life $T_{1/2}^{0}\nu = 1.77^{+0.31}_{-0.11} \times 10^{21}$ yr. An upper limit of $T_{1/2}^{0}$ > 7.91 x $10^{21}$ yr for the half-life of the Majoron mode was derived. The energy resolution in the region of the transition energy $E_{0}$=2038.6 keV is of order 3 keV FWHM. There is no evidence of a peak there, and the limit $T_{1/2}^{0}\nu > 9.1 \times 10^{24}$ yr (90% CL) was derived. A pulse shape discrimination system is being implemented ed. It allows to identify and reject multi-site events, for instance multi Compton scattering events. This reduces the background by a factor 5.

A similar experiment, IGEX (South Carolina, Pacific Northwest, Zaragoza, ITEP, INR collaboration), has now also started producing data. It uses several Ge detectors enriched to 87.4 % in $^{76}\text{Ge}$ in Homestake, Canfranc and Baksan. The reported half-life for $\beta\beta^{2}\nu$ decay is in rough agreement with the Heidelberg-Moscow value. The limit $T_{1/2}^{0}\nu > 5.7 \times 10^{24}$ yr (90% CL) was obtained. Pulse shape discrimination is also being implemented.

$^{130}\text{Te}$. Another calorimeter, of a rather innovative type, a cryogenic bolometer, has been built by the Milano group to study $^{130}\text{Te}$. The central component is a 334 g TeO$_{2}$ crystals mounted in a low background cryostat, and operated at 10 mK. Natural tellurium with 34.5 % $^{130}\text{Te}$ is used. Excellent energy resolution, around 10-15 keV FWHM, is achieved, close to that of Ge detectors. Data have been accumulated in the Gran Sasso laboratory during 10500 hours. No evidence of $\beta\beta^{0}\nu$ decay has been found, and the limit $T_{1/2}^{0}\nu > 2.1 \times 10^{22}$ yr (90% CL) was derived.
9. Neutrino Physics

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
 & T_{1/2}^{0\nu} [\text{yr}] & \langle m_{\nu} \rangle [\text{eV}] & \text{Caltech} & \text{Heidelberg} & \text{Tübingen} & \text{Stras.-Mad.} \\
\hline
\text{direct} & & & & & & \\
\begin{array}{l}
\text{Ge} \\
\text{Te} \\
\text{Xe}
\end{array} & \begin{array}{l}
9.1 \cdot 10^{24} \\
2.1 \cdot 10^{22} \\
4.4 \cdot 10^{23}
\end{array} & \begin{array}{l}
1.2 - 1.3 \\
5.2 - 5.6 \\
2.4 - 2.7
\end{array} & \begin{array}{l}
0.51 \\
4.8 \\
2.2
\end{array} & \begin{array}{l}
0.48 \\
5.1 \\
1.8
\end{array} & \begin{array}{l}
< 1.4 \\
< - \\
< 5.2
\end{array} \\
\hline
\text{geochem.} & 128\text{Te} & 2.6 - 7.7 \cdot 10^{24} & 1.1 - 2.8 & 1.0 - 1.7 & 1.1 - 1.9 & - \\
\hline
\end{array}
\]

Table 9.8: Measured lower limits for the half-life of various $\beta\beta 0$ transitions. Deduced upper limits on the neutrino mass $\langle m_{\nu} \rangle$ using various matrix elements.

Now a 20 crystal detector is being built. Efforts are also made to grow crystals made from enriched $^{130}\text{Te}$.

$^{136}\text{Xe}$ This nucleus is presently being investigated by the Caltech-Neuchâtel-PSI collaboration in the Gotthard underground lab. The detector is a tracking device, to be specific a gas time projection chamber filled with Xe enriched to 62.5% in $^{136}\text{Xe}$. The source mass is 3.3 kg of $^{136}\text{Xe}$. Data were taken during 10'000 hours. The limits $T_{1/2}^{0\nu} > 4.4 \cdot 10^{23} \text{ yr (90\% CL)}$ and $T_{1/2}^{\nu\nu} > 1.4 \cdot 10^{22} \text{ yr have been reported.}$

$^{100}\text{Mo}$. Another tracking device, NEMO II, is being used in the Fréjus lab. The source is a thin foil, stretched in the middle of the fiducial volume filled with He gas and instrumented with Geiger cells. Several nuclei can be investigated. The energy of the electrons is measured in two planes of scintillators. Using a 17g source of Mo, enriched to 98.4% in $^{100}\text{Mo}$, $\beta\beta 2\nu$ decay was observed with the half-life $T_{1/2}^{0\nu} = (0.95 \pm 0.10) \cdot 10^{19} \text{ yr}$. From the same data, a limit $T_{1/2}^{0\nu} > 5 \cdot 10^{20} \text{ yr}$ was derived for $\beta\beta X_0$ decay. The sensitivity to $\beta\beta 0\nu$ decay however is limited because of the small mass of the source. More recently, the NEMO group has also observed $\beta\beta 2\nu$ decay in $^{116}\text{Cd}$, as have the Osaka and Kiev groups.

9.7.2 Matrix elements

The calculation of the nuclear matrix elements for all three modes is quite elaborate. Until recently the most popular method was quasi random phase approximation (QRPA). It is computationally simple. Although crudely, it is believed to include all relevant features of the nuclear structure. Now, in addition, realistic shell model calculations have been performed for a few nuclei. In principle they should describe the nucleus in more details.

9.7.3 Comparison with predictions for $\beta\beta 2\nu$ decay.

Quite firm predictions based on QRPA for $\beta\beta 2\nu$ half lives in various nuclei have been obtained by a group at Caltech. The agreement between measured and calculated half-lives in $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{100}\text{Mo}$, in which $\beta\beta 2\nu$ has been observed directly, is quite good, within a factor 2 or 3. The agreement is also reasonable in $^{128}\text{Te}$ and $^{130}\text{Te}$, for which geochemical data are available.

The Strasbourg-Madrid group has performed realistic shell model calculations for $^{76}\text{Ge}$ and $^{82}\text{Se}$. They too are in reasonable agreement with measured values. Shell model predictions for $^{48}\text{Ca}$, a nucleus which is particularly simple to describe, also reproduce well the measured value.

9.7.4 Interpretation of the data on $\beta\beta 0\nu$ and $\beta\beta X_0$.

The fair agreement between measured and calculated half lives in $\beta\beta 2\nu$ decay suggests that the same modes can reasonably predict the matrix elements for the other decay modes.

Table 9.8 lists the measured $\beta\beta 0\nu$ half life limits from several experiments. For $^{128}\text{Te}$, it was assumed that the geochemically determined half life is a lower limit for that of $\beta\beta 0\nu$ decay. The corresponding neutrino mass limits, using the QRPA calculation of Caltech as well as from two other groups, are shown. The spread between the limits for a given half life is largest for
76 Ge, and relatively small for the other, heavier, nuclei. This spread can be considered a measure of the uncertainty associated with the $\beta^{30}\nu$ matrix elements. The last column gives the limits obtained with the shell model matrix elements of Strasbourg-Madrid.

One sees that the $^{76}$Ge data give the most constraining limit. In all, one may conclude that the various experiments give:

$$\langle m_\nu \rangle < 1 - 1.5 \text{ eV}.$$  

Table 9.9 shows some measured half life limits on $\beta^3\chi^0$ decay and the corresponding limits on $\langle g_{eff} \rangle$ obtained from the more conservative Caltech matrix elements. Here the geochemical $^{128}$Te data are the most constraining. Of the direct searches the $^{136}$Xe experiment gives the most stringent limit. In any event, one may conclude that the effective coupling constant is bound by: $\langle g_{eff} \rangle < (0.5 - 1) \cdot 10^{-4}$.

### 9.7.5 Conclusion and outlook.

To summarise, in recent years the allowed $\beta^{3}\nu$ decay has been observed in several nuclei. QRPA and shell model calculations reproduce fairly well the measured half lives. This gives some confidence that the matrix elements needed to interpret the experimental limits on $\beta^{30}\nu$ decay can be calculated with reasonable reliability as well. Data from the most sensitive experiments on that decay lead to the limit $\langle m_\nu \rangle < 1 - 1.5 \text{ eV}$ for the effective neutrino mass.

The Heidelberg-Moscow and IGEX experiments on $^{76}$Ge are continuing. They may achieve sensitivities of order $T^{3\nu}_{1/2} \simeq 5 \cdot 10^{25} \text{ yr}$ in $^{76}$Ge, corresponding to $\langle m_\nu \rangle \simeq 0.5 - 1 \text{ eV}$. The 20 crystal bolometer array being built by the Milano group will presumably achieve comparable sensitivity, provided background problems can be solved.

The NEMO III detector, for which NEMO II was a prototype, is being built and will be installed in the Fréjus lab. It is based on the same principles, but has a much larger source foil, and has a magnetic field for electron-positron identification. It is designed to study primarily $^{100}$Mo, of which it can accommodate 10 kg. Because of the high sensitivity, but also the modest energy resolution (15% FWHM) and the relatively short $\beta^{32}\nu$ half life in $^{100}$Mo, the major background source when looking for $\beta^{30}\nu$ decay will be $\beta^{32}\nu$ decay! After a few years of data taking, a sensitivity of order $T^{3\nu}_{1/2} \simeq 5 \cdot 10^{24} \text{ yr}$ should be achieved corresponding to $\langle m_\nu \rangle \simeq 0.3 - 0.6 \text{ eV}$.

The MUNU detector, a CF$_4$ gas TPC built for the study of neutrino-electron scattering at the Bugey nuclear reactor, could also be used to search for double beta decay. Installed underground, filled with 10 kg of enriched $^{136}$Xe, it would achieve a sensitivity comparable to that of NEMO III.

One can thus conclude that presently running or planned experiments will explore effective neutrino masses down to, say, 0.3 eV. Independently of what they find, it will be desirable to push further the sensitivity. To achieve this it is necessary to go to yet larger source masses.

Larger detector sizes can be considered. Current double beta decay detectors, even considering NEMO III, are small by many standards. For instance, solar neutrino detectors are significantly larger. Also it does not seem impossible to produce enriched sources with masses as large as 100 kg.

To take full advantage the background will need to be reduced in parallel. This seems possible with the experience gained in present generation double beta decay experiments and solar neutrino experiments. Also detector technology has brought advances leading to better event signature.

Therefore a next generation experiment with a source of 100 kg cf some enriched material appears feasible. It would have a sensitivity to $T^{3\nu}_{1/2}$ of order $10^{26} \text{ yr}$, corresponding to $\langle m_\nu \rangle \simeq 0.1 \text{ eV}$. Such a project can however only be carried out by a large collaboration. Several of the groups presently involved in various smaller experiments would have to join efforts.

To go further, it seems impossible to envision enriched sources. This means that much larger detector masses, and still better event identification are necessary. One idea put forward is
Table 9.9: Measured lower limits for the half-life of various $\beta\beta\chi^0$ transitions. Deduced upper limits on the effective coupling constant $\langle g_{\text{eff}} \rangle$.

to use a liquid TPC filled with natural Xe, in which not only the electrons are detected, but also the positive ions. Much development needs however to be done before the construction of a full scale detector can be considered.

9.8 Dark Matter

9.8.1 Introduction: Basics of Non-Baryonic Dark Matter

There is overwhelming evidence that most of the matter of the universe is dark and a compelling motivation to believe that it is mainly of non-baryonic origin. The matter density of the universe, $\rho$, is currently expressed in terms of its critical density $\rho = \Omega \rho_c$ with $\rho_c = 3H_0^2/8 \pi G$, where $H_0 = 100. h. km^{-1}. Mpc^{-1}$ with $0.4 < h < 1$. Measurements and estimates of $\Omega$ have been made at various scales by a diversity of methods.

The visible stars account only for a small fraction of $\Omega$ ($0.002 \leq \Omega_{v} h^2 \leq 0.006$). As the scale of the observed cosmic structures increase, the resulting values of $\Omega$ become larger, approaching the unity value predicted by inflationary cosmologies. Big-bang nucleosynthesis constrains the baryon fraction of $\Omega_B h^2$ to be within $\sim 0.007$ and $\sim 0.024$, and so baryonic dark matter is needed. On the other hand, the large values of $\Omega$ at increasing scales together with the smallness of $\Omega_B$ imply that exotic, non-baryonic particle dark matter should be the main component of the universe.

Extensions of the Standard Model of Particle Physics provide non-baryonic candidates to dark matter. From the cosmological point of view two big categories of such candidates have been proposed: Cold Dark Matter (CDM) and Hot Dark Matter (HDM) according to whether they were slow or fast moving at the time of the galaxy formation. Their relative proportion is so as to properly generate the observed cosmic structures by gravitational evolution of the scale-invariant primordial density fluctuation. The simple CDM model needs to be mixed with a small fraction of HDM to match the observed spectral power at all scales. The mixed model featuring $\Omega_{CDM} \approx 0.75$, $\Omega_{HDM} \approx 0.2$, $\Omega_B \approx 0.05$ ($h = 0.5$, $\Omega_\Lambda = 0$, $\Omega = \Omega_M = 1$) is one favoured option. Recent values of the Hubble constant ($h \approx 0.7$) might favour however a Cold DM model with a non-zero cosmological constant $\Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$. The typical HDM candidates are neutrinos of a few eV, which could provide the right critical density. The most likely candidate is the tau neutrino $\nu_\tau$. There is no known method proposed so far to directly detect the hot DM relic neutrinos and so terrestrial sources are used to explore this possibility. The discovery of a $\nu_\tau$ mass in the few eV range would favour this form of DM and so several neutrino oscillation experiments are under way to look for such issue. In the CMD sector, typical candidates are heavy Dirac or Majorana neutrinos in the GeV-TeV mass range or other heavy, weakly interacting neutral particles, generically called WIMPs. A distinguished Majorana WIMP is the neutralino -the lightest (and stable) supersymmetric particle of SUSY theories. Accelerator results constrain the neutralino mass, for representative values of its parameter space, to be above 10-20 GeV. Neutrino relic abundances of cosmological interest are in the range $\Omega_\chi h^2 \sim 0.2$. Another celebrated CDM candidate is the axion, a non-thermal relic invented to solve the strong CP problem.
9.8.2 Searches for Non-baryonic Dark Matter. Recent Highlights

Particle Dark Matter can be detected indirectly by searching in cosmic ray experiments for particles produced in the WIMP annihilation in the galactic halos, like antiprotons, positrons or photons, or looking in deep underground detectors (like MACRO, Baksan, Kamiokande and Soudan), or in the projected or ongoing under-water neutrino telescopes (like AMANDA, ANTARES, Baikal, or NESTOR) for the neutrinos emerging as final products of WIMP annihilation in the Sun or the Earth. MACRO in Gran Sasso has searched for such neutrinos (in the GeV-TeV range) by looking for neutrino-induced, upward-going muons coming from the direction of the Sun or the Earth core. The muon flux limit from non-atmospheric origin (in the 25° window) is 3.1 \times 10^{-14} \text{cm}^{-2} \text{s}^{-1} (from the Earth) and of 6.6 \times 10^{-14} \text{cm}^{-2} \text{s}^{-1} (from the Sun), after exposures of 1250 m² yr and 380 m² yr respectively. Indirect searches of neutralinos have been carried out also at Baksan (at 850 m.w.e.) with the scintillator telescope. In 10.55 years of data, the upper bound on the muon fluxes are 2.1 \times 10^{-14} \text{cm}^{-2} \text{s}^{-1} and 3.5 \times 10^{-14} \text{cm}^{-2} \text{s}^{-1} (from the Earth and the Sun respectively). Predictions for the fluxes of such muons in supersymmetric models range in the case of the Earth from about 10^{-14} \text{cm}^{-2} \text{s}^{-1} to 10^{-17} \text{cm}^{-2} \text{s}^{-1} (and somehow higher for the Sun case), and so bounds on the neutralino annihilation rate as a function of the neutralino mass have been obtained and regions of the neutralino parameter space excluded. The above mentioned underwater neutrino telescopes project to enlarge the exposure areas up to 3000 m² or higher and plan to reach the 10^{-15} \text{cm}^{-2} \text{s}^{-1} flux limit. Surfaces larger than 10^5 m² would be suitable devices to search for neutralinos in wide zones of their parameter space and so projects for larger underwater neutrino telescopes (1 km³) are being considered.

Particle Dark Matter can also be detected through its direct interaction with ordinary baryonic dark matter. WIMPs forming the galactic halos could interact with the nuclei of a detector producing a measurable recoil. Semi-conductor detectors of Ge and Si, and scintillators -both solids (NaI, CaF₂, LiF) and liquids (Xe)-have been used so far. The size of the expected signal and the event rate depend on the halo model and on the type of CDM particle. WIMPs, slow moving (≈ 0.001c) and heavy (10 GeV to 1 TeV) could produce a nuclear recoil of a few keV. In the case of WIMP with spin-independent interaction, the typical coherent rates range from 10 to 10³ events per day per kilogram of detector. Even at this rate, the background (due to microphonics, electronic noise and natural or induced radioactivity) can hide the signal in the low energy region of the spectrum where it is expected, and so the results obtained are constrained by the level of background achieved so far in such region. Heavy Dirac neutrinos have been excluded in that way with Ge detectors. Other heavy WIMPs interacting through axial, spin dependent interactions with detector nuclei having non-zero spin (like NaI scintillators), with expected rates in the range from 0.01 to 1 count per kg and day, have been explored to provide also valuable exclusions. More appealing candidates, like the neutralino, are essentially not yet reachable with these detectors at the present stage of development.

The tiny energy delivered and the small rates expected in the WIMP nucleus interaction settle the strategy of the DM direct searches: To use detectors of very low energy threshold and very low background (intrinsic and environmental). On the other hand, only a small fraction of the energy delivered by the WIMP goes to ionization, the main part being released as heat and so, superconductors or thermal detectors should be employed. Such cryogenic detectors will achieve lower energies threshold, almost 100% efficiency and have better energy resolution than the conventional detectors. A further step in the background reduction is the use of mechanisms distinguishing for instance those events due to electron recoils (tracers of the background) from those due to nuclear recoils. Hybrid detectors measuring at the same time the ionization and heat (or the light and heat) produced in the detector, or the use of pulse shape discrimination techniques are pre-
liminary successful attempts in the quest for the background reduction.

The non observance, up to now, of a DM signal in direct spectra results in a $\sigma(m)$ exclusion plot. Distinctive DM features, not shared by the background or by instrumental artefacts, would be the way to unambiguously identify the DM, like the annual modulation due to seasonal June-December variation in the relative velocity Earth- halo or the forward-backward asymmetry in the direction of the nuclear recoil due to the Earth motion through the halo.

Various experimental groups have searched for CDM with Ge detectors: USC/PNL/Zaragoza in Homestake (USA) and Canfranc (Spain), USC/UCB/LBL in Oroville (USA), Caltech/PSI/Neuchatel in Gotthard (Switzerland), and MPI-Heidelberg/Moscow in Gran Sasso (Italy) and TANDEM/USC/PNL/Zaragoza in Sierra Grande (Argentina), with energy thresholds ranging from 1.6 keV to 12 keV, and backgrounds of 0.2 to 2 c/keV.kg.day. Summing up the results of these experiments, it is concluded that the heavy Dirac neutrino is excluded as a DM component for masses ranging from 9-10 GeV (Canfranc, San Gothard), up to 4 TeV (Homestake, Gran Sasso).

In the case of NaI scintillators, the level of background achieved has been steadily approaching and even improving that of the traditionally ultralow background Ge diodes by using selected components of very low radioactivity and incorporating statistical techniques of background discrimination (BPRS Beijing/Paris/Rome/Saclay, UKDMC Imperial College/Oxford/Rutherford and Roma II groups). The $\sigma(m)$ exclusion plots obtained by UKDMC and Rome are essentially similar to that obtained with Ge detectors (spin-independent interactions case) and are one to two orders of magnitude more stringent than that of the Ge for spin-dependent couplings. It can be concluded, roughly speaking, that the present experimental lowest bounds on the rate stand about $R \leq 1$ event/kg day (integrated over a 2 keV window around threshold), both with Ge and NaI. Searches for annual modulation signals have been or are being carried out by various groups with NaI and liquid Xe scintillators [Zaragoza (Canfranc), Roma II (Gran Sasso)]. Experiments with large masses of scintillators are in preparation or starting in Boulby, Gran Sasso and Canfranc.

As far as the use of cryogenic detectors for dark matter is concerned, two types of devices are being developed: bolometers/thermal detectors and superconducting superheated grains (SSG). Thermal detectors measure the increase of temperature due to the energy deposition of the WIMPs at very low T. On the other hand, the signal produced in the metastable, superheated grains as response to the WIMP interaction is due to the disappearance of the Meissner effect when the heat delivered by the particle energy deposition is able to trigger the superconducting to normal phase transition of the grains.

The first bolometer operating underground (Gran Sasso) was that of the Milan group dedicated to double beta decay searches of Tellurium. Large bolometers of TeO$_2$ (340 g.) with NTD Ge-sensors, although optimised for $2\beta$ decay searches, are also producing data for DM (resolution of 1% at 60 keV and background of $\approx 12$ c./keV.kg.day at threshold, $E_{\text{thr}} \approx 10$ keV), which have lead to encouraging $\sigma(m)$ exclusion plots for spin-independent WIMP’s couplings to Tellurium and Oxygen. This group has proved the sensitivity of these bolometers to nuclear recoils. A French Collaboration (EDELWEISS) has performed at Frejus a bolometer experiment with a 24 g. sapphire crystal endowed with an NTD Ge thermistor. Recent improvements of this experiment have produced backgrounds of 25 c./keV.kg.day at low energy. Small sapphire bolometers of $E_{\text{thr}} \approx 0.3$ keV are being explored in Canfranc within a French-Spanish Collaboration, ROSEBUD (IAS/IAP/Zaragoza). The Munich/Garching/Oxford Collaboration has developed thermal detectors with superconducting phase transition thermometers (in indium, indium/gold, tungsten) in various absorbers (mainly sapphire Al$_2$O$_3$) with the purpose of a DM search experiment (CRESST) in Gran Sasso. This Collaboration got, with a 31 g. sapphire bolometer (at 15 mK), an energy threshold
of 0.3 keV and a energy resolution of \( \approx 100 \) keV for 1.5 keV X-rays FWHM, which is the best resolution obtained so far per unit of detector mass. CRESST is being currently installed in Gran Sasso for a first series of sapphire experiments with 4x250 g. crystals.

Low temperature hybrid devices have been developed by the CIPA/Berkeley/Stanford/Santa Barbara Collaboration with Ge bolometers which also collect electron-holes pairs (CDMS experiment). The proof-of-principle of a 70 g. hybrid Ge detector was successful and good discrimination efficiency between nuclear recoils and Compton background was obtained. Also resolutions of 0.7 keV for heat and of 1.6 keV for ionisation at 60 keV were achieved. Background performances (at shallow depth) were 2 e/keV.kg.day in the relevant low energy region. The experiment is producing its first results of a search for WIMPs at shallow depth, and will be soon moved underground to Soudan (USA) with a set of hybrid detectors of Ge and Si. In much the same way, the French Collaboration EDELWEISS has obtained recently very encouraging results with hybrid Ge detectors.

The Bern/PSI/Annecy group (ORPHEUS experiment) and the Lisbon-Zaragoza-Paris Collaboration (SALOPARD experiment) are constructing Superconducting Superheated Grains (SSG) prototype detectors with micrograins of tin for WIMP searches. Other type of Superconducting detectors, like the Superconducting Tunnel Junction (STJ), made very important R+D progresses following the developments of the quasiparticle trapping technique of the Oxford group, but there is not yet any planned STJ dark matter experiment.

9.8.3 Prospects of WIMP Direct Searches.

The quest for the particle dark matter faces formidable tasks. To fulfil the requirements implied by the strategies indicated above, improvements in the radioactive background (both intrinsic and environmental), in efficiency and in energy threshold should be accomplished. The use of radiopure material need to be implemented by that of background discrimination techniques. New, suitable nuclear target should be also tried. The search for modulated, distinctive signatures of WIMPs should be pursued. Most of these requirements will be hopefully fulfilled by sets of cryogenic/hybrid detectors, superconducting detectors or large masses of NaI scintillators or of other conventional detectors endowed with background discrimination, and this line of action is in the objective of the next coming or future experiments.

9.9 Neutrino Masses

The neutrino flavours \( \nu_e, \nu_\mu, \) and \( \nu_\tau \) are defined as weak eigenstates which couple with unit strength to \( e, \mu, \) and \( \tau, \) respectively. These weak eigenstates \( \nu_l \ (l = e, \mu, \tau) \) are not, in general, states of definite mass, but instead are linear combinations of mass eigenstates \( \nu_i, \ (i = 1,2,3), \) hence \( \nu_l = \sum U_{li} \nu_i. \) Here, the unitary matrix \( U_{li} \) describes the mixing strength of mass eigenstates to the corresponding left-handed weak eigenstate. This ansatz is in close analogy to the experimentally observed weak mixing in the quark sector.

9.9.1 Mass limits for \( \nu_e \)

These limits apply to \( \nu_1, \) the dominant mass eigenstate in \( \nu_e. \) They would also apply to any other \( \nu_j \) which mixes strongly in \( \nu_e \) and has sufficiently low mass to appear in the respective decay. The limits are valid for Dirac as well as Majorana mass terms.

The most intrusively investigated process, which allows in principle to determine the rest mass of \( \nu_1, \) is the nuclear \( \beta \)-decay of tritium. Assuming CPT-invariance the results on tritium decays can also be applied on \( \nu_1. \) A non-vanishing neutrino mass would manifestate at the endpoint of the \( \beta \)-spectrum. The decay rate can be written as \( d\Gamma/dE \propto E(E_0 - E)\sqrt{(E_0 - E)^2 - m^2_\nu}, \) where \( E \) is the total electron energy and \( E_0 \) the total energy released in the nuclear transition. Tritium decay is preferred due to its low endpoint energy of 18.6 keV.
The square of the neutrino mass is measured in tritium beta decay by fitting the shape of the beta spectrum near the endpoint. In all of the most sensitive experiments $m_{\nu}^2$ has been found to be significantly negative.

Including the endpoint anomaly, Stooff et al. find a value of $m_{\nu}^2$ which is more than 5 standard deviations negative, and report a Bayesian limit of 7 eV (95\% CL) for $m_{\nu}$ obtained by setting $m_{\nu}^2 = 0$.

The Mainz experiment uses an electrostatic spectrometer with adiabatic magnetic collimation and a molecular tritium source frozen onto an aluminium substrate. At an energy of 137 eV below $E_0$, the value of $m_{\nu}^2$ is found to be compatible with zero within the 1 sigma error bars. An upper limit of 7.2 eV (95\% CL) for $m_{\nu}$ is reported.

The Troitsk group is also using an electrostatic spectrometer with adiabatic magnetic collimation. Their source is gaseous tritium. This search for the neutrino rest mass resulted in $m_{\nu}^2 = -22 \pm 4.8$ eV$^2$ [1]. The negative $m_{\nu}^2$ value may be explained by the local enhancement in the region 7-15 eV below the end point with an integral branching ratio of about $10^{-10}$. Including this anomaly into a fit procedure shifts the measured value to $m_{\nu}^2 = -4.1 \pm 10.9$ eV$^2$, finally leading to an upper limit of $m_{\nu}$ of 4.35 eV (95\% CL) [1].

Results from studies of electron capture transitions from $^{163}Ho$ give limits on the mass of $\nu_1$. This value may differ from $\bar{\nu}_1$ only in absence of CPT-invariance. The best limit is reported by Springer et al.: $m_{\nu} < 225$ eV at 95\% CL.

### 9.9.2 Mass limits for $\nu_\mu$

These measurements apply to $\nu_2$, the dominant mass eigenstate in $\nu_\mu$. The decay of pions $\pi^+ \rightarrow \mu^+ + \nu_\mu$ is the most appropriate process to search for this neutrino mass. In case of pion decay at rest the square of the muon momentum is: $p_\mu^2 = (m_{\pi}^2 + m_{\mu}^2 - m_\mu^2)^2/(4m_{\pi}^2) - m_\mu^2$. A massive neutrino would reduce the muon momentum.

In a recent paper the up to now most precise measurement of $p_\mu$ from stopped pions has been reported. The group at PSI (Switzerland) improved former limits by using a beam of muons originating from the decay of $\pi^+$-mesons stopped at the surface of a pion production target. The muon momenta are analysed by a magnetic spectrometer, the muons are detected by a silicon microstrip counter and a single silicon surface barrier detector.

The muon momentum was measured with great accuracy to be $p_\mu = 29.79207 \pm 0.00012$ MeV/c yielding an upper limit for the neutrino mass of $m_{\nu} < 0.16$ MeV at 90\% CL.

### 9.9.3 Mass limits for $\nu_\tau$

These measurements apply to $\nu_3$, the dominant mass eigenstate in $\nu_\tau$. Upper limits of this mass have been derived from studies of the decay of the tau lepton. The most sensitive results were obtained by fitting the invariant mass spectrum of hadrons produced in tau decays with a likelihood method. Up to now no indication for a finite neutrino mass for $\nu_3$ has been found.

The ARGUS group analyzed 20 events of the decay $\tau \rightarrow 5\pi^\pm \nu_\tau$. CLEO II sampled 60 events of the same type as ARGUS as well as 53 tau decays of the mode $\tau \rightarrow 3\pi^\pm 2\pi^0 \nu_\tau$.

In a recent publication a new limit on the tau neutrino mass of 24 MeV (95\% CL) was reported by the ALEPH group at LEP. Here a two dimensional likelihood fit in the variables invariant mass and energy of the hadrons in $\tau \rightarrow 5\pi^\pm (\pi^0) \nu_\tau$ decays. This method improves the sensitivity with respect to the use of invariant mass alone.

### 9.9.4 Search for Heavy Neutrinos and Neutrino Mixing

Beside the searches for primary neutrino masses a big variety of experiments has been performed looking for neutrino mixing. Inevitable consequences of non-degenerate neutrino masses and mixing are neutrino oscillations, deviations in the spectra of weak decays, and neutrino decays.

For neutrino masses below ca. 1 MeV beta-decay experiments searching for kinks in the en-
nergy spectra of the emitted electron are sensitive down to ca. $|U_{ei}^2| \approx 10^{-3}$.

For neutrino masses above ca. 1 MeV up to 10 MeV the high neutrino flux from nuclear reactors were used to search for the neutrino decay $\nu_3 \rightarrow \nu_e + e^+ + e^-$. Most sensitive limits reached are $|U_{ei}^2| \approx 10^{-4}$.

At higher masses the two-body kinematics in the decay $\pi \rightarrow e\nu$ or $\mu\nu$, $K \rightarrow e\nu$ or $\mu\nu$ is used where the heavy neutrino would cause an abnormal peak in the charged lepton spectrum.

In accelerator experiments again neutrino decay was investigated. Here neutrinos originate from light $\pi$ and $K$ or the heavier $D$ and $D_s$ mesons produced in proton beam dumps.

The LEP experiments investigating the shape of the Z-resonance and searching for neutrino decay exclude a fourth family Dirac neutrino up to a mass of 44 GeV for all mixing elements. A fourth family Majorana neutrino is excluded up to a mass of 38.2 GeV.

In theories beyond the standard model isosinglet neutrinos are discussed which don’t couple to the Z like ordinary neutrinos and hence are not yet excluded. Two searches for heavy isosinglet neutrinos $\nu_H$ have been performed, testing the hypothesis of mixing between isosinglet and isodoublet neutrinos. One experiment, CHARM-II, was looking for neutral current production of $\nu_H$ and its subsequent decay. Another search was done by the LEP experiments where $\nu_H$ is produced in Z boson decays. No evidence for heavy isosinglet neutrinos was found.

Neutrinos which are too heavy to be directly produced at present accelerators still would affect physics at lower energies due to deviation from neutrino universality. The measured neutrino couplings for $\nu_e$, $\nu_\mu$, and $\nu_\tau$ in neutral as well as charged current reactions constrain the sum of non-diagonal elements of neutrino mixing, i.e. $\sum |U_{ei}|^2 < 7.1 \cdot 10^{-3}$ and $\sum |U_{i\mu}|^2 < 1.4 \cdot 10^{-3}$.

9.9.5 Conclusion and Prospect

Groups investigating tritium decay for neutrino mass experiments have undertaken high efforts to understand their spectra. In the next future one may expect solutions for irregularities in the spectral shape in order to be able to set a reliable limit on the mass of electron neutrino below ca. 5 eV. New developments, like the investigation of cryogenic bolometers might allow in future the use of alternative sources as well as new detection methods. Recently, first experimental results on the beta decay of $^{187}$Re achieved with a cryogenic microcalorimeter were presented by the group of Gencva.

A recent measurement on the muon neutrino mass shows improved limits. Furthermore, this result seems to be free now from obsolete pion mass values. However, it might be very difficult to improve existing limits substantially with existing detection techniques.

The same appears for experiments looking for the tau neutrino mass. A new upper limit of 24 MeV has been established. Future experiments at LEP-II and LHC might still improve this constraint.

The search for heavy neutrinos already covers a mass range from a few 100 eV up to $\approx 100$ GeV and is sensitive to even very small mixing amplitudes. Up to now no evidence for a heavy neutrino was found. Future experiments at accelerators are able to extend the mass scale above the Z-mass up to $\approx 150$ GeV.

9.10 Outlook and recommendations

Neutrino physics is presently focused on the crucial problem of neutrino mass. If at least one neutrino has non-zero mass, this would mean evidence for physics beyond the Standard Model. In addition, massive neutrinos would play an important role in cosmic structure formation.

Direct measurements provided until now only upper limits: several eV for $\nu_e$, 0.16 MeV for $\nu_\mu$, 24 MeV for $\nu_\tau$. The double beta decay experiments have given an upper limit of 1-1.5 eV for the average mass of Majorana neutrinos.

At present, the most promising way to obtain evidence for non-zero neutrino masses is to search for neutrino oscillations.
There are three indications of neutrino oscillations: they have been obtained by the experiment LSND and by the study of Solar neutrinos and Atmospheric neutrinos. It is mandatory to continue the experimental activities in these three fields to clarify the situation (LSND) and obtain direct evidences of the neutrino oscillations, if they exist (Solar and Atmospheric neutrinos).

i. Solar neutrinos.

It is imperative to study the energy dependence of the solar neutrino flux and to this purpose a direct measurement of the $^7\text{Be}$ component is necessary. Borexino is the only planned experiment capable of such a measurement.

It is also important to independently demonstrate that the solar neutrino deficit results from neutrino oscillations. This can be achieved in three different ways:

- by detecting time variations of the solar neutrino flux. Seasonal variations, as expected from vacuum oscillations, can be observed with high sensitivity by Borexino, while day-night effects resulting from matter effects when neutrinos traverse the Earth can be observed by Superkamiokande, SNO and Borexino.
- by detecting distortions of the expected energy spectrum, as planned by SNO and by Superkamiokande.
- by measuring the total neutrino flux independently of neutrino flavour, through the detection of neutral current interactions. Such a measurement is planned by SNO at a later phase of the experiment.

Of the three experiments just mentioned, only Borexino is installed in a European laboratory (LNGS). This experiment should receive full support in order to start data taking as early as possible.

Other experiments aimed at improving existing measurements must also be encouraged, such as Supermuonu and Hellaz, which are designed for the spectroscopy of pp, $^7\text{Be}$ and pep neutrinos. GNO will monitor the solar neutrino flux as a function of time over many years, thus detecting, for instance, slow variations associated with possible changes of Sun properties.

ii. Atmospheric neutrinos. The anomalies of the atmospheric neutrinos need a clarification for the multi-GeV data. In addition the hypothesis that the Atmospheric Neutrino problem could be explained by the oscillation mechanism needs a direct investigation, independent from the uncertainties in the predicted atmospheric fluxes. This is the case of the Long Baseline experiments.

A long baseline experiment in Japan will start data taking in 1999 using neutrinos produced by the KEK 12 GeV proton synchrotron and the Superkamiokande detector (the energy of these neutrinos is below threshold for $\tau$ production). Another experiment (MINOS), with a total detector mass of 10 KTon, will use a beam from Fermilab at a distance of 730 km and will probably start data taking in the first years of the next century.

Long baseline experiments have been proposed in Europe, using neutrino beams from CERN to LNGS at a distance of 732 km. At present the only approved experiment which could use such a beam is ICARUS, with a mass of only 600 Tons, but the construction of the beam is not yet approved. This programme must receive full support. We also recommend that any new detector for long baseline experiment be built with good electron identification capability in order to be simultaneously sensitive to $\nu_\mu - \nu_e$ and $\nu_\mu - \nu_\tau$ oscillations.

iii. Short baseline experiment. The LSND result need an independent confirmation. It will only be possible to plan a detailed strategy for a next round of short baseline experiments when the results from the upgraded KARMEN experiment and new data from LSND become available. But also CHOOZ, even less sensitive, is in condition to explore the $\Delta m^2$ region $10^{-1} - 10^{-2}$ eV$^2$ interesting for the atmospheric neutrinos. Therefore both KARMEN and CHOOZ have to be encouraged and supported.
New more sensitive short base-line experiment are surely welcome. We should like to note that the $\Delta m^2$ region above 0.1 eV$^2$ is the region of cosmological importance, because neutrinos with such mass values would represent an important component of dark matter in the Universe.

Another important way to search for neutrino physics beyond the Standard Model is to study the possible neutrino magnetic moment. MUNU is now installed at Bugey and it is expected to have a sensitivity better than the previous experiments by an order of magnitude. This experiment has to be fully supported.

Upgradings and developments in cryogenic detectors have to be strongly encouraged in various fields as: beta decay, double beta decay, dark matter and X-ray spectroscopy.

This technique may provide a very powerful tool for opening a new range of sensitivity in detector technologies with respect to energy resolution and detection threshold.

Experiments on dark matter, using scintillators (as NaI) have to encouraged too; they have a good chance to reach large volumes in relative cheap conditions.

Concerning double beta decay it will be desirable to push the sensitivity below $\sim 0.3$ eV, which is the limit of experiments presently running or being planned. To achieve a sensitivity of $\sim 0.1$ eV, a source mass of $\sim 100$ Kg of enriched material, possibly $^{136}$Xe, is required. This does not seem unrealistic. Improved detection techniques, methods to further reduce the background, must however be developed. R&D in that direction should be encouraged.

Experiments for precision measurements of $\bar{\nu} - e$ scattering are sensitive to fundamental neutrino properties, and of high importance in elementary and particle astrophysics. An improvement of experiments in this field is highly recommended. The sensitivity of these experiments depends strongly on the detection threshold for the electron energy and background. Presently, cryogenic detectors and driftchambers seem to be promising technologies.
10. Fundamental Interactions

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10.1 Introduction

The exploration of the fundamental constituents of matter, of their interactions and of the underlying basic symmetries is an essential part of physics. This exploration is generally considered as the task of Particle Physics. Part of this activity requires however the use of nuclei, the theoretical insight and the instrumentation of Nuclear Physics. It could be named "Nuclear Particle Physics". As a consequence, this field of research, duly considered as part of Nuclear Physics, enters quite naturally into the purview of NuPECC just as nuclear astrophysics, which derives its rationale from astrophysics, benefits from NuPECC co-ordination and care.

Beyond what one may call "nuclear particle physics", we briefly discuss also in this report rare reactions or decay-modes of pions and muons. They are conceptually equally important approaches to the exploration of fundamental symmetries and share with nuclear particle physics some of its research environment. Like double beta-decay they even exploit sometimes coherent effects in heavy nuclei. It would be detrimental for physics if this intellectually so important "intermediate energy" activity would somehow "fall in the cracks" between Particle and Nuclear Physics.

It is a common prejudice that the exploration of the fundamental constituents of matter, at smaller and smaller dimension scales, requires the ultimate energies of the highest energy particle accelerators. It is expected that novel particles observed at these accelerators will provide the clue to a unified description of Nature. We hope to illustrate in this brief report that nuclear particle physics on the "high precision" frontier provides results complementary to those we expect at the "high energy" one. This is so because of the multiple quantum-states provided by nuclei and the possibility to perform experiments of very high precision in a nuclear physics environment. Instead of observing directly the novel particles, one pins them down by observing their tiny influence on low-energy processes. Many recent review papers stress the complementarity of the two approaches.

The common struggle of Particle Physics both at high energies and at low energies in the nuclear environment is to find new physics beyond the Standard Model. This model is surprisingly successful but is not believed to be the ultimate description of nature because, among other reasons, of the many ad-hoc parameters it introduces.

Some indications of new physics are just on the horizon, as is discussed in the first part of this report. Some such earlier hints were discarded following closer scrutiny. What should be stressed, however, is that in the dynamics of this search, ingenuity always pushed the precision-frontiers to new unprecedented limits. To mention some examples, the dipole moments of atoms and that of the neutron now reach the $10^{-25}$ e-cm limit and are expected to be improved even further by two orders of magnitude. This tiny dipole moment would correspond, on the scale of the Earth, to a deviation of a couple of microns from sphericity!

Some decay-modes of muons forbidden by the Standard Model will be observed at the $10^{-12}$-$10^{-13}$ level if some attractive scenarios of new physics beyond the Standard Model turn out to be correct. This will require years of experimentation with muon fluxes of a few $10^8$ per second provided by proton-accelerators of several hundred kW.

Symmetry-tests and rare-decay searches explore energy-domains in the range 1-100 TeV.
Particles of such a large mass may show up in processes which are strictly forbidden in the Standard Model (e.g. violating lepton number), or may signal one of the more natural generalisations of the Standard Model like the left/right symmetry.

10.2 Fundamental symmetries

Tiny violations of the fundamental symmetries may be a fingerprint of new interactions or particles. Low energy studies of feeble interactions provide access to virtual particles with masses in the TeV range. Precision studies in this field require powerful facilities with the most intense beams of muons, slow neutrons, protons, deuterons and radioactive nuclei. European laboratories like the Paul Scherrer Institute (PSI), the Institute von Laue Langevin (ILL) or CERN’s ISOLDE have created a basis for the forefront symmetry studies.

In the following we shall not strive for completeness and review only part of this very active field.

10.2.1 Parity violation

At present, the intriguing question is whether the weak interaction violates parity in a maximal way. The left-right symmetric extensions of the Standard Model restore parity symmetry at energies which exceed significantly the mass-equivalent of the hypothetical right handed $W_R^\pm$ bosons.

Measurements of the relative polarisation of leptons, emitted anti- and parallel to the spin direction of the parent, bear enhanced sensitivity for effects induced by $W_R^\pm$'s. This method has already been applied successfully in nuclear beta decay. $^{12}\text{N}$, $^{17}\text{F}$, $^{21}\text{Na}$, $^{107}\text{In}$ nuclei are a subject of refined or new investigations at CERN (ISOLDE), PSI, and in university laboratories such as Louvain-la-Neuve. A new study of this kind is in progress at PSI for muon decay.

Recent discrepancies in the absolute beta decay asymmetries in free neutron decay should be soon resolved in a series of experiments with cold neutrons decaying in the beam. In the future these experiments will be supplemented by studies with ultra-cold neutrons polarised to almost 100% and stored in bottles and traps.

A particularly elegant alternative, insensitive to the Standard Model uncertainties and systematic effects, is provided by a simultaneous measurement of the emission asymmetries of the electron and neutrino with respect to the neutron spin.

The next series of parity violation experiments at low energies with polarised muons, neutrons and nuclei will provide results in excess of 500 GeV/c² for the mass of the right handed bosons. For certain theoretical scenarios such limits are difficult to reach in measurements at high energy colliders.

Precision - experiments on atomic parity-violation (Cs, Fr, ...) probe the Z²-coupling and so provide results complementary to the ones obtained at high energy.

10.2.2 Time reversal

Cosmological development of the Universe requires existence of hitherto unknown mechanisms of CP or T violation. New T-violating phenomena may be generated e.g. by a Θ-term in QCD interactions, or by the exchange of leptoquarks, Higgs or right handed weak bosons with complex couplings.

T-violating correlation experiments determine spin polarisations and/or momenta of the particles involved in the decay process. The systems studied include the muon, neutron, $^{8}\text{Li}$ and $^{19}\text{Ne}$ nuclei, $K^+$ and $K^0$ mesons, $Λ^0$ and Σ-hyperons; and recently even polarised $Z^0$. The achieved accuracies reach $10^{-3}$ in the T-violating amplitudes with respect to the regular weak interaction strength. Here, progress is achieved by a combination of new experimental techniques and development of the premium quality polarised beams and targets. T-violation in muon decay will be further investigated at PSI. New experiments with slow neutrons are in development at National Institute of Standards and Technology (NIST)-USA, and at the spallation neutron source under commissioning at
PSI.

These studies determine the complex amplitudes of the vector, axial vector, scalar or tensor weak interaction terms, which are related to the coupling constants and masses of the exchanged new gauge bosons. We quote the limits of $3 \text{ TeV/c}^2$ from beta decay for the mass/amplitude ratios in lepto-quark exchange.

T-violating electric dipole moments (EDM) arise at the Lagrangian level from the QCD’s $\Theta$ term. In other theories, nonzero EDM’s are induced e.g. via higher order processes (quantum loop corrections).

Classical EDM tests are performed with polarised free neutrons. Present experiments restrict the neutron EDM to values less than $1.1 \times 10^{-25} \text{ e cm}$. Results on atomic EDM close to the above limit have also been obtained using complex systems: Hg and Tl atoms, or TIF molecules. New, challenging ideas are pursued to improve the sensitivity by three orders of magnitude. The complexities of the new experiments call for large international collaborations. Studies have already begun in the USA and Japan in the context of new spallation sources.

The new EDM experiments will either establish a finite effect, or reject some popular theories such as Weinberg’s multi-Higgs or left-right symmetric models.

### 10.2.3 Other tests

In addition, we refer to novel approaches to parity violation in hadronic interactions or tests of time reversal in neutron transmission and optics. Scalar interactions are hunted for at ISOLDE-CERN, and experiments combining techniques of atomic and nuclear physics (electromagnetic or optical traps with radioactive nuclei) might soon provide access to observables involving heavy recoil particles.

### 10.2.4 Conclusions

Studies of symmetry violations have certainly a potential to find the so desperately sought for physics beyond the Standard Model. Though the subjects discussed use methods of nuclear and particle physics, the basic symmetries are of more general interest, extending into the fields of atomic and molecular physics, modern cosmology, quantum chemistry, biology, and even general education.

#### 10.3 Rare muon- and pion-decay modes

Two kinds of processes must be distinguished: a) processes with a finite rate where precision experiments try to measure small deviations from the prediction of the Standard Model, b) processes which are absolutely forbidden within the Standard Model. Experimentally the latter have essential advantages: i) there is no Standard Model background. Therefore, if other backgrounds can be avoided the sensitivity improves linearly (not by square root) with measuring time, ii) there is no need for a very accurate absolute calibration. High particle fluxes at intermediate energies can be obtained at so-called particle factories (meson [pion]-, B-meson-, $\tau$-lepton factories). Especially at pion factories extremely high fluxes of muons are available, which are very useful for rare decay studies because of the following reasons:

- a) in many models beyond the Standard Model (but not e.g. in Higgs related ones) the branching ratios are independent of the mass of the decaying particle. Since muon fluxes of $> 10^8/s$ are available, the highest sensitivities to exotic physics are obtained for muon decays.

- b) the quality of present muon beams is very high, they have low energy (e.g. surface muon beams with $28 \text{ MeV/c}$ momentum, allowing target thicknesses of a few tens of $\text{mg/cm}^2$), small contaminations of pions and positrons, and small phase space (beam spots of $2 \times 2 \text{ cm}^2$).

- c) in most cases there is only one well-known physics background, which on the one hand can be suppressed by good enough detector resolutions, and on the other hand can be used as an independent normalization.
Presently two new experiments are being discussed, the interest coming from several theoretical papers predicting measurable rates on the basis of supersymmetric grand unification schemes. There is a letter of intent for a new $\mu$-e conversion experiment submitted to BNL which aims to reach a sensitivity of $10^{-16}$ and enjoys highest priority ranking. The other experiment is $\mu \rightarrow e\gamma$. The design of a detector largely depends on the outcome of the MEGA experiment at the Los Alamos Meson Factory (LAMPF). The only place where enough muons with sufficient quality are available ($>10^8/s$) to obtain a sensitivity of $10^{-14}$ is PSI. The interest in pion decays concentrates on pion beta decay. Although other rare pion decays ($\pi \rightarrow e\nu\gamma$, $\pi \rightarrow 3e\nu$, $\pi^0 \rightarrow e^+e^-$) also yield valuable information, pion beta decay will eventually improve our knowledge of the $V_{ud}$ matrix element of the CKM matrix.

To summarise, we find that rare decays and especially rare muon processes have a great discovery potential for fundamentally new physics. Thanks to progress in accelerator and detector technologies, they also have the possibility of achieving further important improvements in sensitivity.

### 10.4 Recommendations

The continued availability of high intensity pion, muon and cold neutron beams for the study of fundamental symmetries and rare decays is recommended. The further development of trapping techniques at high-yield targets of radioactive atoms is also recommended.
Bibliography


