

Section.6 : Facilities and technical developments

Development of new facilities and experimental opportunities is essential for research in all of natural sciences. In recent decades the atomic physics and material science communities, which use particle beams, have often exploited nuclear physics facilities. Accelerators, detectors, and target developments which were motivated by nuclear physics needs, found useful applications here. This situation has now changed somewhat: now one finds devices, which were developed within the atomic physics and material science community, being increasingly also applied in nuclear physics. Among those are: synchrotron radiation facilities, free-electron lasers, high-power optical lasers, traps for cooling atoms and ions, highly charged ions and selective ionisation sources. These developments demonstrate the effectiveness of a healthy cross-fertilisation between the disciplines.

A few of these developments, selected from those involved in the experiments previously presented in the chapter, will be briefly described in this section.

6.1 Ion Beam Facilities

6.1.1 Ion sources

New ion source developments involve both the production of very **Highly Charged Ions** (HCI) and the **selective production of singly charged ions**.

6.1.1.1 Highly charged ion sources

Sources for highly charged ions are based on electron impact ionisation of gas atoms, plasma clouds, or injected low charged ions. The well-known Electron Cyclotron Resonance (ECR) ion source, Electron Beam Ion Source (EBIS), and Laser-plasma ion source have been developed further to high degree of performance and reliability. They have the following typical characteristics:

ECR: high intensity dc beams (μA) of medium charged ions;

EBIS: medium intensity pulsed beams (10^7 particles/pulse) of highly charged ions

Laser-plasma ion source: high intensity pulsed beams (10^9 particles/pulse) of medium charged ions

An interesting possibility is also the further development of Electron Beam Ion sources and Traps (EBIT) with electron beams reaching 300 keV to ionise effectively U atoms completely.

For nuclear physics, a main application of highly charged ions is still improving the effectiveness of acceleration and deceleration in accelerators. EBIS and ECR sources are used as ionisation boosters in radioactive beam facilities. Externally produced isotopically pure or radioactive singly charged ions are injected into an ECR or EBIT for breeding the charge state to higher values for further acceleration or for trapping. The charge breeding efficiency is rather high, in the order of 10-30%. This type of beam production is already being studied at GANIL with the SIRA (Source d'Ions Radioactifs) facility, which is the test -bench of the target-ion-source system of SPIRAL (for Système de Production d'Ions Radioactifs et d'Accélération en Ligne). Charge breeders for accelerating radioactive beams in compact Radio Frequency Quadrupole accelerators are going into operation (e.g. at REXISOLDE). These will probably be combined with laser ionisation to enhance the selectivity for radioactive isotopes. Highly charged ions are exploited for high-precision mass measurements

in traps (SMILETRAP in Stockholm), and for mass determinations of radioactive nuclei in storage rings (ESR at GSI). In both cases the systems rely on the high charge state and on the fact that the systematic errors can be reduced with charge dependent measurements. A strong activity is atomic spectroscopy in few-electron atomic systems, which relies on the availability of highly charged ions at almost any velocity and in any abundance. Very heavy highly charged ions in large abundance are needed for studies of nuclear-atomic decay modes, e.g. bound-state beta decay and hyperfine transitions.

Unique features of ultra-slow HCI are exploited in fragmentation of atoms, molecules, and clusters with fragment-momentum imaging in recoil-ion spectrometers. HCI are employed as probes for solid surface investigations.

A previously applied technique for obtaining slow HCI in complex accelerator structures is undergoing a revival: the accel-decel technique. Presently, GSI explores the possibility of efficiently producing extremely highly charged ions up to bare U^{92+} ions at very low kinetic energies. In this so-called HITRAP project, relativistic ions are stripped in a foil, and after injection into the storage ring ESR they are cooled and decelerated to 3 MeV/u. The ions are then extracted and decelerated further in a linear decelerator and brought into a Penning trap for cooling further. It is expected that about 10^4 ions per second of, for example, U^{91+} can be obtained basically at rest in this way. A fair number of such ions are expected to be cooled to 4 K.

6.1.1.2 Special sources for low-charged ions

Isobar-selective ion sources should deliver isobarically clean beams with a short pulse length at low charge state. High intensity ion sources for negative ions will be needed in the future, mainly H^- sources for producing mA currents of H^- for applications in neutron spallation sources and beam plasma heating. There is, of course, still a need for special negative ions for tandem-accelerator operation.

Laser ion sources that are wavelength tunable for selective ionisation should be further improved in sensitivity and effectiveness. More sophisticated techniques as presently applied, such as Doppler-free techniques and continuous wavelength lasers instead of broadband-pulsed lasers are to be exploited to improve the selectivity. With these new laser ion sources one could have pure beams of any isotopes of Cu, Fe, Ag, ... at e.g. ISOLDE.

Ion sources for cluster beams are in use now and are being developed further to produce even highly charged cluster ions. This will allow the presently available range of velocities to be extended upward for cluster beams by efficient acceleration, which is important for several applications.

6.1.2 Acceleration devices: recent developments and projects

The availability of high-performance ion storage rings, swift ion and cluster accelerators producing intense beams with high optical quality and ion sources providing highly charged slow ions has enabled a series of benchmark experiments on particle – matter collisions. Beside important technical improvements in ion beam production, mainly two types of devices open the way to new results in atomic and condensed matter physics:

6.1.2.1 Cluster accelerators

Besides the standard sputter-ion sources, which deliver high energy cluster beams, Liquid Metal Ion Sources (LMIS) such as those operating in Orsay and Lyon have significantly increased the available beam current for metallic clusters like Au_n . Gold LMIS

allow the acceleration of very heavy gold cluster beams (Au_{20} to Au_{400}) to a total energy of 10 MeV/q, extending considerably the range of projectile size for cluster-solid interaction studies. A new type of molecular ion source has also been developed at the IPN-Orsay. It will deliver multiply charged poly-atomic ions of high mass (10000 to 100000 u) at 10-50 keV/q. The multiple-ionisation of large molecules or clusters is achieved with an ECR source combined with various injectors of neutral or low-charged molecular ions (gas, oven, LMIS...). To reach higher energies, this type of source should be installed on a high-voltage platform.

6.1.2.2 Storage rings

Heavy-ion storage rings with magnetic confinement are now widely used for atomic and molecular ions, both negatively or positively charged. In recent years, the electron coolers of these rings were pushed to the limit of energy resolution by the very effective beam-expansion method. Having the coldest beams in the merged beams configuration, they are expected to play an important future role also in electron-ion collision experiments.

A new type of storage rings and traps has recently appeared: electrostatic storage rings and traps. These are especially suited for very heavy molecular and cluster ions, where the mass-to-charge ratio is too large for a magnetically confining heavy-ion storage ring. In the electro-static devices, however, the species cannot be stored at sufficiently high energy to match the speed of the electrons of the electron cooler in the merged-beams configuration of the rings. Crossed-beam set-ups are being prepared for studies of electron interactions with gas-phase bio-molecular ions and cluster ions in electrostatic storage rings. In the future, we can expect to see systems of double rings as well as rings completely cooled to liquid He temperature for cooling internal degrees of freedom of clusters and molecular ions.

6.2 Neutron Beam Facilities

6.2.1 Experimental Reactors

Five neutron centres have been built or refurbished in Europe in the past 10 years, and are likely to remain operational without major investment at least for another 15 years. These are: the Institute-Laue-Langevin (ILL) Grenoble, France, the ISIS Facility, Didcot, UK, the BER-II at Hahn-Meitner-Institut (HMI), Berlin, Germany, the SNQ at Paul-Scherer-Institut in Villigen, Switzerland and the BRR at KFKI, Budapest, Hungary. In addition, a new research reactor is being built in Munich, Germany. Further lower-flux reactors, which run under less tight time schedules, are still currently requested for student training and isotope production in medical and materials science applications. Most recently the use of so called super mirror coatings in neutron guides is revolutionising neutron beam extraction and delivery, producing 5 – 7 fold beam intensity gains on the sample.

6.2.2 Ultra-cold Neutron Sources

Ultra-cold neutrons (UCN) are neutrons with energies low enough to be totally reflected from many material surfaces under all angles of incidence. Typically, they have velocities below 7 m/s. They can be trapped in materials or in magnetic and gravitational traps, and they serve as tools for fundamental physics experiments. The precise measurement of the neutron decay lifetime and the search for an electric dipole moment (EDM) of the neutron are the flagship experiments of UCN physics. The EDM experiment, in particular, is considered one of the most important low energy particle physics experiments.

Over the last 15 years, the Institute Laue-Langevin provided the most intense source of UCN. At present, it is the only relevant UCN source in the world. However, there are strong

new efforts to build next-generation UCN sources in the US, in Japan, and in Europe. There are two major source projects in Europe, one at the new Munich reactor FRMII in Germany and one at the Paul Scherrer Institute (PSI) in Switzerland. Both projects are based on solid deuterium converters to produce UCN from cold neutrons. The FRMII source will use the continuous cold flux from the reactor, while the PSI source will use pulsed neutron production on a dedicated spallation target. Both projects have the potential to become the world leading facilities within the next few years. Both aim at increasing the available UCN density by about two orders of magnitude and the intensity by one or two orders of magnitude. Great improvements for fundamental particle physics experiments can be expected. Moreover, the increased UCN density and intensity might open up new fields of applied research.

6.2.3 Spallation Source Projects

For a long time Europe was the world leader in neutron scattering science. The US is attempting to catch up by a spallation source project, which is currently aimed at building a facility very similar to ISIS in the UK but with a strongly enhanced power, up to 2 MW compared to 160 kW. This neutron source, SNS, should go on line by 2007. In December 2000, the Japanese government approved a similar project to be realised by about 2005 in Tokai, Ibaraki province. The basic difference between the US and Japanese projects is that the first calls for a facility essentially exclusively devoted to neutron scattering research, while it is envisaged in Tokai that the power of a large proton LINAC, which will ultimately exceed 10 MW after several stages of enhancement, will be shared for a variety of uses, including neutron scattering, nuclear waste transmutation development and nuclear physics.

Since 1992, a consortium of European research centres and universities has been studying the construction of a powerful new spallation source for neutron scattering research, the European Spallation Source (ESS). A feasibility study completed in 1997 concluded, that a 5 MW facility could be built for about 1000 M€. A central ESS project team was installed in 2000 at FZ Jülich to co-ordinate the decentralised research, development and design efforts of the consortium members. The goal is to present a detailed updated proposal by the end of 2003 to the European governments that calls for completing ESS in year 2010. Based on the French proposal CONCERT, an alternative is also under study to realise ESS following the Japanese model as one of the facilities housed on an up-to-25-MW proton LINAC. In order to realise this concept, a liquid metal target is under consideration, for which recently the MEGAPIE (Megawatt Pilot Target Experiment) initiative was launched by Commissariat à l'Energie Atomique (France) and Forschungszentrum Karlsruhe (Germany) in collaboration with Paul-Scherrer-Institute (Switzerland) to demonstrate the feasibility of a liquid lead-bismuth target for spallation facilities at MW beam power levels. The realisation of ESS will preserve the leadership role of Europe in neutron scattering studies of condensed matter, in the face of US and Japanese advances which are in the process of realisation. Without an ESS-class facility, this leading position would fade away in the next decade.

6.3 Exotic Beam Facilities

Two widely complementary μ Spin Resonance (μ SR) user facilities are operational in Europe: (a) The continuous-beam facilities at the Laboratory for μ on-spin spectroscopy (LMU) at the Paul Scherrer Institute (PSI) in Villigen, Switzerland and (b) the Pulsed Muon Facility (PMF) at ISIS (CLRC) in Oxfordshire, UK.

Other facilities exist in the world, which are currently providing muons for materials and chemical analysis. Besides these centres, the Joint Institute for Nuclear Research in Dubna, Russia, and CERN in Geneva, Switzerland have developing programs for implementation of

muon factories. Important technical achievements in recent years are the development of low-energy muon beams and the extraction of one muon at a time from a continuous beam at PSI.

Recently, the availability of MeV positron beams at the Stuttgart MPI für Metallforschung has allowed new experiments leading to the characterisation of transient processes involving positrons and positronium.

6.4 Radioactive ion beam (RIB) facilities

6.4.1 Developments

There is a need for technical developments concerning beams produced by ISOL facilities having increased intensity, energy and elemental/isotopic variety.

ISOLDE at CERN is the best example, and it is continually evolving. However, for some specific cases, other institutes with different production methods can be complementary, provided that adequate investments on targets and beam intensity are given.

The SPIRAL, based on the ISOL method, will provide production and separation of radioactive beams at GANIL. The radioactive atoms are ionised by an ECR source and are subsequently accelerated by a K=265 cyclotron to energies between 1.7A MeV and 25 A MeV. The charge states of the accelerated ions are typically 9+ for Ar and 15+ for Kr beams. The ejection energy of the ion source is between 12 q keV and 34 q keV. The installation of a dedicated beam line at this energy should permit the implantation of radioactive ions for solid-state studies. These studies are already possible (but with low beam intensities) at GANIL in the SIRA facility.

Energetic radioactive ion beams with controlled energy ranging from few eV up to MeV are needed. Particularly in solid-state physics, a tunable beam energy opens new possibilities, e.g., to reach a specific layer in a multilayer system, to reduce the local concentration of implanted ions by performing series of implantation with different energies, and to reach the active depletion layers in semiconductors, outside the surface defects and space charge region.

6.4.2 Radioactive nuclei accumulators

As in the case of mass spectrometry in storage rings, fast cooling of hot fragments should be achieved by stochastic cooling in a dedicated accumulator and cooler ring for measurements of very short half-lives by the time-of-flight-technique. For measurements of long half-lives by the Schottky technique, an optimised storage ring should provide efficient electron cooling and detection. In the latter case resonant pick-ups for the Schottky signal should be further developed in order to increase the signal-to-noise ratio. Clearly, higher intensities of radioactive ion beams as planned for the second-generation RIB facilities are crucial.

Beam cooling and bunching techniques are prerequisites for efficient use of RIB. The segmented ion cooler (SIC) devices will be essential elements for beam improvement with respect to time structure and emittance. The techniques should be further developed to reach nearly 100% transmission efficiency in the cooling as well as in the bunching mode with short residence time in the SIC. Stopping of relativistic ion beam in gas cells and its combination with a SIC will enable ISOL-type experiments to be performed with ions at rest or at an energy of some 10 keV also at in-flight facilities where the reaction products have an energy of several 100 MeV/u. Here and in the case of the SIC, systems have to be developed which provide a closed cycle for the noble gas of extreme purity used to stop the relativistic ion beam and to cool it.

6.5 Developments of micro-beams

Nuclear microprobes have well-established applications in materials analysis and microfabrication. There they provide a rich area of research for small groups having relatively modest budgets. Microprobes have large versatility, and there is an ever-increasing number of material subjects to study. Consequently, there is a multitude of laboratories in Europe equipped or being equipped with ion micro-beam facilities. The obviously desirable technical developments are improved energy stability and 3D spatial resolution.

With the advent of radioactive beams, there will be request for getting *radioactive micro-beams* for material research. Such beams will soon be available at European radioactive beam facilities: ISOLDE facility at CERN/Geneva; the ISL at the Hahn-Meitner Institute / Berlin; the cyclotron and isotope separator of the ISKP/Univ. Bonn; and the SPIRAL facility at GANIL/Caen.

6.6 Laser Beam Facilities

6.6.1 Free-Electron Lasers

Novel electron accelerator techniques can be used to create free-electron lasers (FEL) in a wide wavelength interval extending to the x-ray region. Generally it is the case that the shorter the wavelength, the higher the electron energy necessary. For an infrared FEL one uses today typically 50 MeV electrons whereas for a X-ray laser 1 GeV electrons are needed. X-ray FELs are therefore developed at large accelerator facilities (DESY Hamburg, Stanford, Brookhaven). The wavelength ranges from mm to μm and from VUV to X rays are of special interest. Due to the coherent emission via the self-amplified spontaneous emission (SASE) process, very large intensities can be obtained, with peak brilliance ten orders of magnitude higher than in conventional synchrotron radiation. This is accompanied by very short pulse structures (in the fs regime). The pulse structure is a direct consequence of the electron-beam time structure, it can therefore be varied over a large range, taking advantage of modern accelerator technology. A unique example is the TESLA facility of DESY, Hamburg. This, in contrast with competing facilities (SLAC, USA and KEK, Japan) is based on highly advanced super-conducting technology. TESLA, a 33 km long e^-e^+ collider integrates the SASE X-ray laser complex. These machines therefore open completely new prospects for sciences that study material and molecular structures as well as their dynamics, using the time resolution, wavelength, and brightness. Three-dimensional imaging, with phase sensitive holography and very high space-time resolution will be possible. These studies will elucidate the structures of atoms, molecules, crystals, and materials in femto-second snap-shots.

6.6.2 High-Power Laser Systems

The tremendous advances in producing intense short-time laser pulses in the visible wavelength regime at several facilities can be expected to reveal completely new phenomena in atomic physics, accelerator physics, and material sciences. In Europe, particularly in France and Germany, a number of excellent high-intensity lasers exist. In the short-pulse high-intensity mode, they will be able to focus hundreds of TW power on a few- μm spot on the target. A peta-watt laser system has so far only been realised with NIF at LLNL, USA. At GSI the PHELIX project provides a kJ high-power laser that will be combined with a heavy-ion beam simultaneously focused on the same spot, in order to reach even higher power densities or to study time evolutions in the plasma. The main motivation for these intense lasers is the study of high-temperature highly unstable plasma physics and developments of drivers for inertial-confined fusion devices.

These laser facilities are beginning to bear fruit in the spectroscopy of few-electron highly-charged ions, in a new access to study atomic and molecular fragmentation dynamics, and in providing high-intensity short-time x-ray pulses or in driving an x-ray laser in the future. This again is due to the large abundance of highly charged ions produced in the plasma. The use of plasma heating is being considered for new types of particle accelerators. In material science, exist the exciting option to produce and to study for the first time metallic hydrogen in a laboratory. This is expected to form when the very high-density compression is reached with the short-pulse high-intensity mode of these facilities.

6.7 Instrumentation

6.7.1 Ion Traps

Traps for ion mass spectrometry should be further developed in two branches: One is aiming for extremely high precision mass determinations. This requires cooling of highly charged ions in a Penning trap, either resistively or by electrons or positrons. A development in that direction is followed at SMILETRAP and HITRAP. The other branch will be non-destructive single-ion identification and single-ion mass measurements by the Fourier-Transform Ion Cyclotron Resonance (FT-ICR) technique. This will only be possible by operating the trap, as well as the electronics for detection of image currents induced by the orbiting ion, at liquid-helium temperature. This development is essential in the case of rare events such as found in the region above $Z = 100$.

Superconducting magnets with considerably higher fields than presently available, but still very homogeneous, will lead to higher accuracy or enable access to shorter-lived nuclei. Along these lines, the use of higher harmonics to excite cyclotron motion should be investigated. Furthermore, the efficient transfer of the ions under investigation into Penning traps is a central issue for further studies. Stopping and cooling techniques (gas cells and segmented ion coolers) should be further explored with respect to achieving the highest efficiencies and shortest periods of time for cooling and bunching the ions. This is a special challenge in the case of gas cells for stopping relativistic fragment beams.

Another type of trap is also of primary interest for the study of fundamental interactions: the Laboratoire de Physique Corpusculaire of Caen has built a transparent Paul radioactive ion trap (PIF –for Piège-Interactions-Fondamentales). Here, the goal is to study the beta-neutrino angular correlation in a beta-decay process for singly charged ions. This trap will be installed on a future low-energy line of SPIRAL.

6.7.2 Target developments

Rapid developments in target preparation techniques occurred recently by utilising atomic traps and cold supersonic jets. The development of atom traps by the atomic physics community has led to various applications within the field of nuclear physics. First of all the ensembles of cold atoms can be used - similarly to those from supersonic jets - as thin targets for collision experiments, also suitable for storage rings. For example, at TSR in Heidelberg a target of cold Li atoms is being developed for monitoring the spatial profile of the circulating ion beams. Moreover, the detection of collisionally induced reaction fragments with high spatial, momentum and energy resolution (as in recoil-ion momentum spectroscopy) allows the study of collision processes in much detail. Perhaps most promising is the possibility to investigate decay processes of accelerator-produced radioactive atoms in a trap with unprecedented completeness and accuracy: With spin-polarised nuclei practically at rest the complete kinematics of the decay process - including the neutrino - can be obtained by measuring the electron or positron in coincidence with the recoil nucleus. Corresponding

experiments are now being prepared at various places in the world with the goal of looking for physics beyond the Standard Model.

6.7.3 *Detector developments*

6.7.3.1 *Particles and photon detectors*

There are two areas in detector developments urgently needed by the community where some progress can be reported :

- The first one concerns the development of **two-dimensional position sensitive detectors** for electrons, ions, neutral particles, photons, etc. They should be equipped with fast readouts, cover a large detection area, and be able to handle high count rates, with multi-hit capabilities. Such detector systems would be needed tailor-made around high-power lasers or intense ion beams. They would be also very useful for experiments involving low intensities of radioactive beams or trapped ultra-cold highly charged ions. Finally, they could detect the emission of radioactive samples with short half-lives. Such a detector made of a 256-anode array coupled to standard channel plates has been developed at Orsay to study the interaction of fast and large clusters with solids. This device, associated with dedicated time encoding electronics, allows the simultaneous measurement of 256 time-of-flight spectra on an event-by event basis, triggered by the same start signal. It provides the mass identification and the localisation of several hundreds of ions emitted under a single impact with repetition rates of several kHz.

- The second one is dedicated to effective high-resolution detectors, which have a wide spectral coverage. There is a growing need for these types of detection devices for X rays, charged, or neutral particles. Promising developments have begun based on the **bolometric or calorimetric principle**. For example, in these detectors a photon is converted in an absorber to phonons, which lead to an accurately measurable temperature rise. The temperature rise is amplified by the low heat capacity of the absorber at a very low temperature, and by the high sensitivity of the thermistor used to measure the temperature rise. So far a resolution of 8 eV at 6 keV x-ray energy is reached. The size of the absorption chip is, however, only a few μm square, so that an array of such chips is required for efficient photon detection. The resolution is mainly governed by thermo dynamical fluctuations in the absorber and the Johnson noise in the thermistor. At present, it is still hard to control these parameters for a large array of such detector chips. That problem should be solved in the near future. One would then have a powerful detection system for many applications in heavy-ion research, such as Lamb-shift spectroscopy, nuclear reactions with radioactive beams with fast mass spectroscopy, energy analysis of heavy ion channeling experiments, etc.

6.7.3.2 *Neutron detectors*

An important factor determining the neutron data collection rates is the solid angle around the scattering sample covered by detectors. Here the advances with cost-effective position sensitive, pixel detectors present a real breakthrough. The recently commissioned neutron spectrometer at ISIS has a total of 16 m² detector area covered with 2.5-cm-resolution detectors position sensitive in both dimensions on a quasi-spherical surface segment of 6 m radius. This amounts to detector solid-angle coverage of 0.44 sterad. On modern neutron diffractometers up to 4 – 8 sterad detector coverage has also been achieved. A particularly spectacular breakthrough has been attained at ILL by adapting the cheap image plate technology to Laue-type single crystal neutron diffraction work, primarily for small biological samples. The LADI detector covers close to 4π solid angle with a resolution of about 10⁸ pixels.