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Contents

Editorial ...................................................................................................................................................................... 3
Erratum .......................................................................................................................................................................... 4

Laboratory Portrait
AD—A Laboratory for Low Energy Antiproton Physics
  by Dieter Grzonka and Walter Oelert ...................................................................................................................... 5

Feature Article
Two-Proton Radioactivity: New Insights into the Atomic Nucleus
  by Bertram Blank ........................................................................................................................................... 14

Facilities and Methods
The n_TOF Facility at CERN: A New Approach to Quests in Astrophysics and Technology
  by Franz Käppeler and Alberto Mengon ............................................................................................................. 21
Polarized Radioactive Beams and Nuclear Moment Measurements for Exotic Nuclei
  by Koichiro Asahi ........................................................................................................................................... 28

Impact and Applications
The Nuclear Microprobe
  by M. B. H. Breese ........................................................................................................................................... 33

Meeting Reports
The 23rd Particle Accelerator Conference
  by Shane Koscielniak ........................................................................................................................................... 38

News and Views ................................................................................................................................................ 40
Calendar .................................................................................................................................. Inside Back Cover

Cover illustration: Layout of the AD ring with extraction beam lines and individual photographs from the experiments ALPHA (bottom right), ASACUSA (bottom left), ATRAP (top left), and ACE (top right) with a sketch of AEGIS. The picture in the center shows a typical laser frequency comb setup based on the technique developed by T. Haensch (Nobel Prize in Physics 2005) which is now a basic element in the low energy antiproton experiments (see article on 5).
Editorial

The step from concept to demonstration for three promising, frontier particle acceleration methods—Fixed-Field Alternating-Gradient (FFAG), Energy Recovery Linacs (ERLs), and Plasma Wake Field Accelerators (PWFA)—has been lengthy: FFAGs, ERLs, and PWFA were first conceived in the 1950s, ‘60s and ‘70s, respectively. But recently they have all become credible devices—thanks in part to the rise of parallel technologies, particularly computer simulations. The U. Kyoto FFAG has made the first ever demonstration of Accelerator-Driven Sub-Critical Reactor (ADSR) operation, and the compact non-scaling FFAGs are poised for widespread medical applications if only they can solve the problem of fast-swept RF. For the first time, detailed plans are being developed for several ERL-based light source user facilities, and PWFA have demonstrated 50 GeV energy gains. Along with the super conducting RF technology adopted by the International Linear Collider, these new methods point the way to the future. Contrasting, with the exception of industrial applications, the breadth of accelerator applications has not grown during the same half century. Actually, there was no need: from the outset, accelerators have been involved in nuclear and high-energy physics, and in medical diagnostics and treatment, and in materials and life science, and in defense. What has grown is the depth and prowess of the applications, and the ubiquity and criticality of the accelerators themselves. For example, the precision and sensitivity of structural analyses made on single molecules is unimaginable without them. Accelerators have become a mainstay of modern science, and their use will grow more widespread. This sense of vitality was eminently reflected in the tremendous success of the 2009 Particle Accelerator Conference (PAC09)—a report of which appears in this issue.

The confluence of those two themes, the increasing use and tailoring of accelerator applications and the emergence of new accelerator types, poses a collateral challenge: How to sustain an adequate supply of accelerator physicists and engineers to meet the growing demand? This is not a new issue. The CERN, U.S., and other accelerator summer schools starting in the mid 1980s were a response to this problem, but the severity is now exacerbated. Those schools were successful in training a generation of students, including myself, but now a larger volume of scientists and a wider range of specializations is needed. I believe this demand can only be addressed if accelerator science courses become more widespread in university curricula, and stronger relationships are forged between accelerator laboratories and academia to secure interesting research projects for students. To accomplish that will take determination and cooperation. Fortunately, “collaboration” is a hallmark of our field and we shall be playing to our strengths.

SHANE KOSCIELNIK
TRIUMF, Vancouver

The views expressed here do not represent the views and policies of NuPECC except where explicitly identified.
Erratum

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GABRIELE-ELISABETH KÖRNER
NuPECC

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POST-DOCTORAL FELLOWSHIPS FOR NON ITALIAN CITIZENS IN THE FOLLOWING RESEARCH AREAS

THEORETICAL PHYSICS (N. 15)
EXPERIMENTAL PHYSICS (N. 20)

The INFN Fellowship Programme 2009/2010 offers 35 (thirtyfive) positions for non Italian citizens for research activity in theoretical (n. 15) or experimental physics (n. 20).
Fellowships are intended for young post-graduates who are under 35 years of age by November 15, 2009.
Each fellowship, initially, is granted for one year and then, may be extended for a second year.
The annual gross salary is EURO 28.000,00.
Round trip travel expenses from home country to the INFN Section or Laboratory will be reimbursed, also lunch tickets will be provided for working days.
Candidates should choose at least two of the following INFN sites, indicating their order of preference.

- INFN Laboratories:
  Laboratori Nazionali di Frascati (Roma), Laboratori Nazionali del Gran Sasso (L’Aquila), Laboratori Nazionali di Legnaro (Padova), Laboratori Nazionali del Sud (Catania);

- INFN Sections in the universities of:
  Bari, Bologna, Cagliari, Catania, Ferrara, Firenze, Genova, Lecce, Milano, Milano Bicocca, Napoli, Padova, Pavia, Perugia, Pisa, Roma La Sapienza, Roma Tor Vergata, Roma Tre, Torino, Trieste.

The research programs, must be focused on the research fields of the Section or Laboratory selected (http://www.infn.it).
Applications, in electronic form, must be sent to INFN no later than November 15, 2009.
To register, candidates must use the website:
http://www.ac.infn.it/personale/fellowships/
The application form requires:
• statement of research interests;
• curriculum vitae;
• three reference letters (specifying name, surname and e-mail of each referee).
Theoretical fellowships must start from September to December 2010. Requests for starting earlier accepted.
Experimental fellowships must start no later than April 2010. Requests to posticipate accepted.

ISTITUTO NAZIONALE DI FISICA NUCLEARE
IL PRESIDENTE
(Prof. Roberto Petronzio)
AD—A Laboratory for Low Energy Antiproton Physics

The Anti-proton Decelerator AD is embedded in the accelerator complex of CERN, the international scientific organization established for the purpose of collaborative research founded in 1952 as: Conseil Européen pour la Recherche Nucléaire (CERN) and operated since 1954 as: European Organization for Nuclear Research (Organisation Européenne pour la Recherche Nucléaire). CERN is located near Geneva and hosts the world’s largest particle physics laboratory. Besides the main research focus of experiments at the large hadron collider LHC, a variety of other topics are covered, like low energy anti-proton physics.

After the first pioneering experiments with anti-protons as secondary particles and the anti-proton-proton collider experiments in the SPS, a dedicated ring for low energy anti-proton experiments (LEAR) started operation in 1983. After about 12 years a very successful experimental program was completed.

Despite the original decision of CERN in 1995 to stop the anti-proton program completely, actual results like the high precision measured charge-to-mass ratio for the anti-proton and proton [1], the unexpected finding of meta-stable anti-protonic helium atoms [2], and the first observation of the production of anti-hydrogen atoms [3] turned the intended closing into a reduction of the LEAR complex but keeping a facility for very low energy anti-proton physics by the construction of the anti-proton decelerator AD [4].

The motivation is to use anti-protons as sensors in anti-protonic atoms as well as the investigation of anti-hydrogen atoms. In these experiments atomic transition frequencies are measured with extremely high precision which allows very sensitive tests of interactions and their invariance.

With the first AD beam three experiments were installed, two of them (ATHENA [5] and ATRAP [6]) aiming for the production, trapping, and study of the physics of anti-hydrogen atoms and the ASACUSA experiment [7] to investigate the properties of anti-protonic nuclei.

In addition, the ACE [8] experiment was installed for exploring biological effects of anti-protons on living cells, aiming in the long term for cancer therapy.

At present all experiments are still active with extended setups and experimental programs, where the ATHENA group split into ALPHA [9], following ATHENA’s proposal and AEGIS [10] being accepted by the CERN research committee in fall 2008 aiming for a validity test of the weak equivalence principle by measuring the gravitational force between matter and anti-matter.


A very recent summary of physics with very low energy anti-protons can be found in the proceedings of the workshop “Opportunities in the Physics Landscape at CERN” held in May 2009 [12].

Instrumentation

The Anti-Proton Decelerator—AD

In order to continue an important part of the LEAR physics program the anti-proton production target area and the Anti-proton Collector (AC) remained in their original locations, and the AC ring, see Figure 1, was upgraded to the Anti-proton Decelerator (AD).

The AD is a storage ring of 182 m circumference. Its construction was started in 1997, and the physics program began in 2000. The AD is the only source of slow anti-protons in the world. Anti-protons are produced by bombarding a metallic target (e.g., Iridium) by protons accelerated to 26 GeV with the proton synchrotron (PS) of CERN.

After capturing the anti-protons at a momentum of 3.57 GeV/c in the AD ring they are stochastically cooled and
decelerated to a momentum of 100 MeV/c with intermediate cooling levels at 2 GeV/c and 300 MeV/c to compensate the emittance growths during deceleration. The basic AD cycle with its different intermediate levels of phase space cooling is sketched in Figure 2.

AD spends about 90 seconds to decelerate the anti-protons down to 100 MeV/c momentum, which corresponds to 5 MeV kinetic energy, which is about 10% of the light velocity. Some $3 \times 10^7$ anti-protons, about 75% of the injected particles at 3.57 GeV/c, are ejected in a bunch length of $(150 \pm 50)$ ns at the end of the deceleration cycle.

The experimental areas are located inside the AD-ring, as shown in Figure 1, which is shielded such that the users are allowed to access the area during the anti-proton production, deceleration, and operation.

**Further Deceleration at the Experiments**

An essential condition for the success of experiments at AD is the availability of a high-quality anti-proton beam at very low energies that requires a further deceleration of the anti-proton beam. At ALPHA and ATRAP this is done by letting the anti-protons pass through a metallic foil that is unfortunately connected with a huge loss of these expensive particles. Depending on the actual trap configuration only about 0.1% of the AD bunch can be used in the experiment.

The ASACUSA collaboration has constructed and installed a decelerating radio frequency quadrupole (RFQD) to decelerate the anti-protons from the kinetic energy of 5 MeV down to a kinetic energy adjustable between 110 keV and 10 keV. This RFQ transports about 25% of the anti-protons to the experiment but the emittance is rather large.

**ELENA—a Possible Extension**

The formation of anti-hydrogen typically requires a large number of low energy anti-protons at high densities that cannot be achieved at the present anti-hydrogen experiments with a single AD bunch. Stacking techniques are used to increase the number of trapped anti-protons. However, with lower energy of the anti-protons delivered from the AD much higher trapping efficiencies would be possible. Therefore an upgrade of the AD by adding an extra low energy ring for deceleration down to 100 keV is proposed [13]. The efficiency of the experiments would be hugely improved. The productivity and the availability of the unique user facility AD at CERN with its great scientific potential would be largely enhanced if a further deceleration and cooling storage ring would be installed between the AD and the experiments, even when comparing to the RFQD installation at the ASACUSA experiment due to the additional cooling of the ring. The layout of this extra low energy anti-proton ring ELENA is shown in Figure 3.

ELENA would increase the phase space density at 100 keV by one to two orders of magnitude, depending whether the experiments are using the RFQD already or not, respectively.

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**Figure 2. Basic AD deceleration cycle.**

**Figure 3. Layout of the ELENA ring to be situated between the AD and the experiments.**
Penning Traps

In order to perform very low energy anti-proton experiments like anti-hydrogen studies Penning traps are used to catch the charged particles. Penning traps use strong homogeneous axial magnetic and quadrupole electrical fields to confine charged particles radially and axially, respectively. In practical applications charged ring electrodes are used to create the electric potential, which is a reasonably good approximation for the required quadrupole field and allows an easy transfer of particles into the trap. A schematic drawing of a single Penning trap together with the single particle orbits derived from an ideal harmonic potential distribution is shown on the left side of Figure 4 together (right side) with a typical trap configuration as employed by ATRAP. Depending on the polarity of the trapped particles the center electrode has a higher (for negatively charged particles) or a lower (for positively charged particles) potential compared to the outer electrodes. The electric field causes charged particles to oscillate harmonically along the trap axis, the axial oscillation, whereas the magnetic field is responsible for the cyclotron movement perpendicular to the magnetic field. The coupling of axial and cyclotron oscillations results in a modified cyclotron frequency and an additional slow magnetron movement. The cyclotron frequency depends on the particle charge/mass ratio, and by measuring the cyclotron frequency very accurately the mass can be determined with highest precision if parameters like the magnetic field are well under control.

High precision measurements require a further reduction of the antiproton energy by another 6 orders of magnitude from the keV region, the typical maximum trap potentials, down to the meV region.

For the trapped anti-protons in general as a first step electron cooling is applied where a cloud of electrons is loaded into the trap, which cool via synchrotron radiation to the surrounding temperature. Other cooling techniques to remove energy from particles in a Penning trap are buffer gas cooling, resistive cooling, laser cooling, and radiative cooling. Buffer gas cooling relies on collisions between the charged particles and neutral gas molecules. In resistive cooling, moving image charges in the electrodes are made to do work through an external resistor, effectively removing energy from the oscillating particles. Laser cooling can be used to remove energy from ions with an appropriate electronic structure in Penning traps. Radiative cooling is the process through which
the moving charges lose energy by creating electromagnetic waves due to their acceleration in the magnetic field. This process dominates the cooling of electrons and positrons but is negligible for heavier particles.

Ioffe Traps

Penning traps are of course only useful for charged particles but do not work for neutral atoms like anti-hydrogen. For performing precision tests between matter–anti-matter features, such as spectroscopic comparisons or investigations of gravitational forces, these objects also have to be confined in a trap. The magnetic moment of anti-hydrogen can be used to create a potential well. However, this force is rather weak and accordingly the trap depths are shallow, demanding the temperature of the neutral particles to be trapped to be as low as possible. Typical trap depths achievable are in the order of 1 T, which corresponds to a temperature of 0.67 K.

The simplest configuration for a magnetic gradient field in three dimensions is a Ioffe trap, a magnetic quadrupole field trap with two solenoid fields, so-called pinch coils. A blow up, its composite, and the encapsulated device of a Ioffe trap used in the ATRAP experiment is pictured in Figure 5.

Physics Motivation

Almost every object observable is made out of matter rather than anti-matter. It is general consensus that this baryon asymmetry is the result of only one extra matter particle per billion matter–anti-matter particle pairs imbalance in the production or survival-rate of matter over anti-matter particles in the early stage of the development of the universe.

The apparent asymmetry of matter and anti-matter is one of the most challenging problems in physics. Whether regions made entirely out of anti-matter exist [14] is unknown. From our present knowledge it’s very unlikely since annihilation radiation that should be emitted from the boundary between matter and anti-matter galaxies is not observed.

Research on fundamental symmetries is a very important part of modern physics programs. The CPT theorem demands that for each particle (or element) the equivalent anti-particle (or anti-element) has the same mass, lifetime, spin, and isospin but an opposite value for all of the additive quantum numbers. The proof (or disproof) of the validity of this basic symmetry may be the key to such fundamental aspects as the matter–anti-matter asymmetry in the universe. Physics is still in a phase where it is important to accumulate high precision experimental data from different leptonic and/or hadronic systems. The role of matter–anti-matter comparisons is significant and powerful.

There is in fact growing interest in CPT and Lorentz violation on the theoretical side, based for example on extensions of the Standard Model [15] and involving Quantum Gravity [16], which is important to be accompanied by experimental developments. A comparison of the well-known hydrogen spectral lines (especially the 1S–2S transition) with those of its anti-hydrogen counterpart is a unique opportunity for a direct test of CPT symmetry in a combined particle system. Equally, a direct verification of the validity of the weak equivalence principle—by measuring the gravitational force between matter and anti-matter—allows a unique and new test of our understanding of gravity.

A deep insight into our understanding of physics properties and laws has been given by the studies of invariances of discrete symmetries. The current assumption that reality is invariant under CPT transformation is
based in large part on the success of quantum field theories. These are invariant under CPT as long as reasonable assumptions for causality, locality, and Lorentz-invariance are made. Gravity has not yet fit into a quantum field theory, but theoretical investigations of possible CPT-violations are appearing in the context of the new approach of string theory. Any deviation from an absolute CPT-invariance would indicate new physics. Until now, differences in masses, charges, lifetimes, and magnetic moments of particles and their antiparticles led only to upper limits, as documented in Figure 6.

An improved CPT test is a very important motivation for experiments that compare anti-hydrogen and hydrogen when long-term goals of experiments at the AD are realized, because it is eventually more stringent than any existing test with leptons and baryons only.

The question of CPT as well as Lorentz invariance in atomic systems will be tackled with the experiments proposed at the AD of CERN. Here the tools are the measurements of optical and microwave transitions in anti-hydrogen to be compared to those from the hydrogen atom.

**Anti-Matter and Its Particles**

The building blocks of nature are the six quarks (up, down, strange, charm, bottom, top), the leptons (electron, muon, tau) with their neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$), and the corresponding anti-quarks and anti-leptons.

Particles and their antiparticles can be produced in pairs out of energy generated, for example, in accelerator particle collisions and can be converted back to energy via annihilation.

The existence of anti-particles was first postulated in 1928 by Paul Dirac as a consequence of the Dirac equation. The first antiparticle ever identified, the positron, was seen in 1932 in the cosmic radiation by C. D. Anderson. The anti-proton was discovered in 1955 by E. Segré and O. Chamberlain, and in 1996 the production of the first $11 \pm 2$ anti-hydrogen atoms was announced [3], implementing the SLAC/Fermilab concept [17]. This result was soon confirmed at Fermilab by producing approximately 60 anti-hydrogen atoms [18]. These first anti-hydrogen atoms were produced at very high kinetic energies and were not suited for detailed studies. The aim of AD anti-hydrogen experiments is to produce and trap cold anti-hydrogen. In late 2002 both the ATHENA [19] and the ATRAP [20] collaboration announced the creation of the first “cold” anti-hydrogen atoms.

**Experiments**

**Cold Anti-Hydrogen**

The basic goal of ALPHA and ATRAP is trapping of anti-protons and positrons in separate Penning traps, mixing of the two particle species to produce anti-hydrogen, trapping of anti-hydrogen in a magnetic trap, and spectroscopic studies of the anti-hydrogen atoms.

**Anti-Hydrogen Production.**

The anti-protons from the AD pass through a degrader optimized in thickness for highest trapping efficiency and enter the Penning trap in a bunch of 200 ns. The trap is closed at the end with a potential of a few keV, and anti-protons with energies below the trap potential are reflected. Before they can leave the trap the entrance is closed by a potential. While oscillating back and forth the anti-protons cross a cloud of pre-loaded electrons and since these cool themselves via synchrotron radiation the anti-protons finally are cooled down to the environmental temperature of typically 4.2 K (liquid Helium).

After cooling into the small electron well the trap can be opened many times for other anti-proton bunches from the AD to accumulate the desired anti-proton number for the anti-hydrogen production experiments.

After a sufficient cooling time the anti-protons are transferred into the mixing trap. Before that operation the electrons are removed by a series of fast pulses. A positron plasma cloud is generated in a positron accumulator prior to injection where the source of positrons is the radioactive sodium $^{22}$Na. The positrons are then trans-
ferred to the mixing trap and a nested well configuration is prepared with a short positron well embedded within a long anti-proton well, see Figure 9.

In the anti-proton-positron cloud further Coulomb collisions result in additional cooling of the anti-protons and as soon as the positrons and anti-protons approach a thermal equilibrium anti-hydrogen atoms begin to form. Since they are electrically neutral objects the anti-hydrogen atoms are not affected by the trap fields any more and will leave it. On good days the collaborations produce on the order of 40,000 anti-hydrogen atoms per experiment, which lasts about one hour.

When mixing anti-protons and positrons several mechanisms may contribute to the anti-hydrogen production. In general, due to energy and momentum conservation, a third reaction partner is needed to form a bound anti-proton–positron system like a photon in radiative recombination or another positron in the three body recombination process.

At thermal equilibrium the rates for radiative recombination scales as $1/T^{1/2}$ while for the three particle recombination a rate estimate follows a $1/T^{9/2}$ law, which is the dominant mechanism at low temperatures.

Radiative recombination tends to produce more bound anti-hydrogen atoms with principle quantum numbers between $n = 1$ to 10, whereas the three particle recombination produces excited anti-hydrogen atoms up to very large principle quantum numbers.

The production of usable anti-hydrogen states is still an experimental challenge regarding both, very low temperature as well as tightly bound systems, preferentially down to the ground state.

For detailed studies anti-hydrogen atoms are needed in their ground states but at least the quantum number level should be known precisely. A way here would be the laser-stimulated radiative recombination, which is supposed to have a large cross-section. The ATHENA collaboration attempted to stimulate the radiative process. To produce anti-hydrogen states with the principal quantum number $n = 11$ a carefully tuned intense carbon-dioxide infrared radiation laser was used during the positron–anti-proton mixing stage. For not yet understood reasons no

![Figure 10. Outside (a) and cross-section (b) view of the ring electrodes from the Penning trap, overlayed by the quadrupole Ioffe trap.](image10)

![Figure 11. Distribution of annihilation vertices without (a) and with (b) magnetic octupole field.](image11)
enhancement was observed for the production rate of anti-hydrogen. The interaction of $p$ with positronium ($e^+ e^-$) atoms should allow the production of anti-hydrogen atoms with a well defined quantum number. First suggested by B. Deutsch [21], M. Charlton [22] pointed out that the reaction rate would be enhanced dramatically if highly excited states of positronium could be used. This idea has been implemented by E. Hessels and co-workers [23].

Figure 7. Sketch of the antiprotonic Helium atom with the corresponding level scheme including radiation dominated (red), Auger-dominated (blue), and ionized state levels.

Anti-Hydrogen Detection. The electrically neutral anti-hydrogen is not confined any more when being produced in an electrical potential well. Consequently it will leave the trap without barrier if a magnetic gradient field does not prevent it from doing so. Getting in contact with the matter wall of the trap the anti-atom will annihilate, resulting in a few charged and neutral mesons. In coincidence, the positron from the anti-hydrogen atom will annihilate with a regular matter electron into two 511 keV gammas. This anti-atom annihilation signature was used by ATHENA [19] as is demonstrated in Figure 8 showing clearly the signals of charged mesons and the two gammas.

In principle this method for detecting anti-hydrogen atoms is never free of background. The annihilation of the anti-proton happens on a nucleus of the gold plated electrodes and results mostly in the production of lots of secondary particles including high energy $\gamma$’s converting to electron-positron pairs. Therefore the anti-proton annihilation may lead to the same annihilation pattern as the anti-hydrogen annihilation. ATRAP developed a different scheme [20] for registering the produced anti-hydrogen atoms, see Figure 9.

To start positron cooling and $\tilde{H}$ formation, the $\tilde{p}$’s, stored initially at electrode T2, are launched into the nested Penning trap by pulsing from the solid to the dashed potential in part (b) of Figure 9 for 1.5 $\mu$s. The $\tilde{p}$’s oscillate back and forth through the cold e$^+$ cloud and lose energy via collisions with the positrons, which cool via synchrotron radiation to the 4.2 K of their surroundings. The ionization well at the electrode EET in Figure 9 is constructed such that its electric field ensures that $\tilde{p}$ from the nested Penning trap cannot get into it, except it travels about 4 cm bound within a $\tilde{H}$ atom. Electric fields ionize high $\tilde{H}$ Rydberg states. Numerical modeling indicates the capture of $\tilde{p}$ from $\tilde{H}$ atoms that ionize in electric fields between 35 and 95 V/cm, which corresponds to principal quantum numbers above $n = 43$ to $n = 55$. Only signals from $\tilde{H}$ are detected with this field-ionization method; there is no background at all. Part c of Figure 9 represents 657 ionized $\tilde{H}$ atoms captured in the ionization well during the course of this experiment.

Anti-Hydrogen Trapping. In order to trap anti-hydrogen atoms in an efficient way the production of anti-hydrogen has to be done
within a magnetic gradient field. But this destroys the homogeneity of the axial magnetic field, which guarantees stable confinement of the charged particle clouds $\beta$ and $e^-$ needed to produce $\bar{H}$ atoms. The trapped particle clouds can be considered as a non-neutral plasma stabilized by its rotation (i.e., by the angular momentum conservation that is destroyed by magnetic field gradients).

Using the trap in Figure 10 it has been demonstrated with clouds of up to about 500,000 $\beta$'s that substantial numbers of $\beta$'s survive the radial magnetic field of a quadrupole magnetic trap—enough to produce $\bar{H}$ atoms within this field. In fact $\bar{H}$ atoms were produced within a quadrupole Ioffe trap that is superimposed on a short nested Penning trap [25].

A further reduction of charged particle losses due to the magnetic field gradients can be achieved by employing higher multi-pole orders for which the magnetic field stays low on the trap axis and thus secures the axial symmetry. The field increases toward the electrodes more steeply than a quadrupole field while having essentially the same effective trap depth. The ALPHA collaboration uses an octupole field and has also seen indications for anti-hydrogen production within the octupole field by comparing the distribution of anti-proton annihilation vertices at full octupole field to the distribution without field where anti-hydrogen production has been observed (see Figure 11).

The proof of trapped anti-hydrogen will be one of the next essential steps in these experiments.

The disadvantage of higher multi-pole fields is the low focusing of the atoms, which are much better localized in a quadrupole field. Presently a magnetic trap with an overlay of a quadrupole and an octupole structure is under construction for ATRAP, which allows to trap in an octupole field and to compress the atoms after laser cooling in the quadrupole field.

A further development is the cusp trap of the ASACUSA collaboration for anti-hydrogen ground-state hyperfine spectroscopy [26]. Here a special non-uniform magnetic field is expected to provide either a cloud of spin-polarized anti-hydrogen atoms and/or an energy-filtered spin-polarized ground state anti-hydrogen beam, which can be used to determine the magnetic moment of the anti-proton through hyperfine transition measurements.

**Antiprotonic Helium**

The antiprotonic helium atom ($\bar{p}$-He⁺) consists of an electron and antiproton both bound by the Coulomb force to the helium nucleus. Samples of these objects are readily created by stopping an anti-proton beam in helium gas. In Figure 12 a sketch of the antiprotonic Helium atom is shown with the related level scheme. Using special techniques for resonating high precision laser beams with anti-proton transitions in these exotic atoms the ASACUSA collaboration was able to measure several of these objects. If CPT invariance between the properties of the proton and the anti-proton is assumed, the agreement between experiment and expectation is a signature of the excellence of theoretical treatments and calculation techniques of the three-body Coulomb system including QED corrections. If, on the other hand, the calculated values have to be modified, the degree of deviation gives a stringent test of the fundamental constants of the anti-proton and therefore tests the CPT theorem.

A detailed description on the experimental studies of the ASACUSA collaboration has been recently published in this journal [27].
Anti-Matter as Energy Source

In anti-matter–matter annihilation the entire rest mass of the particles is converted totally into kinetic energy. The energy per unit mass is about 10 orders of magnitude larger than chemical energy and about 3 orders of magnitude larger than nuclear energy produced in nuclear fission or fusion reactions. Thus, the combination of anti-matter and matter constitutes the highest conceivable energy density. Still, for reasons of costs and storage an application for energy consumption as power-plant or rocket propulsion is infeasible and impossible, despite the long history of anti-matter in the science fiction literature (e.g., Angels & Demons by Dan Brown). For about 10 μg anti-hydrogen, which would be sufficient to switch on a 60-Watt light bulb for a few days, costs of hundreds of millions of Euros are estimated [28].

Outlook

It appears that the community of physicists is going to have a brilliant future.

Not only will the high energy frontier advance rather soon as CERN puts the LHC into operation, at the opposite energy scale the AD provides a basic facility for high precision low energy anti-proton physics. These two fields of research will benefit from each other. This unique field of research will even be strengthened by a completely new project on the horizon, the anti-proton complex under construction at FAIR foreseen to deliver medium energy and very low energy anti-proton beams of high brilliance [29].

Scientists and the general public are learning more about fundamental physics. They will get deeper inside nature and will see better how it works. We have to thank all who have contributed to this inspiring future.

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Two-Proton Radioactivity: New Insights into the Atomic Nucleus

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Radioactivity recently turned 110 years old. But still today large parts of its different facets are still to be explored. From the relatively simple experiments of its discoverer, the Frenchman Henri Becquerel, using photographic plates, to the highly sophisticated experiments carried out today, much work has been accomplished leading to the discovery of nine different types of radioactivity. The most common of these decay modes, \( \alpha \), \( \beta \), and \( \gamma \) radioactivity, are widely used today in applications ranging from medicine, over archaeology to wine dating and much more.

The latest radioactivity, discovered in 2002, is two-proton radioactivity, the simultaneous emission of two protons by an atomic nucleus. This radioactivity was predicted almost 50 years ago by the Russian theoreticians V. I. Goldanskii [1] and Y. B. Zel’dovich [2] who suggested that extremely proton-rich nuclei are no longer able to bind all protons. Proton-rich nuclei with an odd number of protons were supposed to emit a single proton, whereas nuclei with an even number of protons were expected to emit, due to the nuclear pairing effect, pairs of protons. According to Goldanskii’s definition, two-proton radioactivity can only occur if the one-proton emission branch is energetically forbidden. In addition, he required somewhat arbitrarily a lifetime of \( 10^{-12} \) s for the decaying state to call its decay radioactivity.

After the observation of proton emission from excited states [3], one-proton radioactivity, that is, proton emission from a nuclear ground state, was discovered more than 25 years ago at the GSI laboratory in Germany in experiments at the SHIP velocity filter by Hofmann et al. [4] and at the on-line separator of GSI by Klepper et al. [5]. It has turned since into a powerful tool to study the evolution of nuclear structure beyond the proton drip-line. Many observables studied with one-proton radioactivity for the most proton-rich nuclei are only accessible by these means [6]. Although predicted by Goldanskii and Zel’dovich at the same time as one-proton radioactivity, two-proton radioactivity was discovered only more than 20 years later in the decay of \(^{45}\text{Fe}\), the sole reason being that the two-proton emitters are much more exotic, that is, much more proton-rich than the one-proton emitters and therefore by far more difficult to produce. This is due to the same fact of nuclear forces that makes two-proton radioactivity possible, the nuclear pairing.

A Short History of the Discovery of Radioactivity

Radioactivity was discovered in 1896 by Henry Becquerel who observed that photographic plates were blackened by uranium ores without “activating” them by sunlight. Rutherford classified the activity observed by Becquerel into two categories: \( \alpha \) and \( \beta \) rays. In 1900, Paul Villard observed an additional radiation, the emission of high-energy photons, as we know today, due to a re-arrangement of the nucleons inside the nucleus, which was termed \( \gamma \) radiation. Marie Curie coined the name radioactivity for these phenomena to express the fact that, unlike, for example, fluorescence radiation, the substances that exhibit these radioactivities are emitting the radiation without being activated.

The \( \beta \) radiation observed by Becquerel and studied by Rutherford turned out to be electrons created in the nucleus when transforming a neutron into a proton. It is accompanied by the emission of a neutral particle, the anti-neutrino. In 1934, Irène and Frédéric Joliot-Curie discovered the reverse process, the transformation of a proton into a neutron with the emission of a positron and a neutrino. Therefore, we distinguish today \( \beta^+ \) and \( \beta^- \) radiation.

In 1938, Otto Hahn and Fritz Strassmann discovered nuclear fission, a decay mode where a heavy atomic nucleus splits into two pieces of similar size. This fission can be spontaneous, that is, it happens without any external influence on the nucleus, or it can be induced, for example, by the capture of a neutron by the heavy nucleus. This nuclear decay mode has by far the largest energy release of all nuclear decay modes and is used today in nuclear power
plants, but also in nuclear bombs. However, due to the large variety of different isotopes produced, fission is also a powerful source for the production of rare isotopes. Indeed, laboratories like ISOLDE, ISAC, GSI, RIKEN, or in the future SPIRAL2 at GANIL and CARIBU at Argonne use fission as a production mode for neutron-rich nuclei.

These radioactivities are now known for many decades. However, it was also clear that these radioactivities may not be the only decay modes of unstable atomic nuclei. As the theoretical understanding of nuclear structure and the experimental techniques progressed, physicists have proposed and discovered new “exotic” decay modes of the atomic nucleus. In 1980, Moe and Lowenthal \[7\] discovered that $^{82}$Se decays by the simultaneous emission of two electrons. In fact, this nucleus and, as we know today, many others, decay or are expected to decay by double $\beta$ decay, a decay mode where two neutrons are simultaneously transformed into two protons with the emission of two electrons and two anti-neutrinos. This decay mode is allowed in the framework of the Standard Model of particle physics because it conserves the lepton number and is today observed for 10 isotopes ranging from $^{48}$Ca to $^{238}$U. For about 60 nuclides, this decay mode could, at least theoretically, exist. Another decay mode, yet to be observed, is the neutrino-less double $\beta$ decay, where only two electrons are observed in the exit channel.

In $\alpha$ decay, a light $^4$He nucleus is emitted. In fission, two medium mass (mass number $A$ of the order of 70–170) are created. A phenomenon situated in between these two decay modes is cluster emission, where a heavy nucleus emits a nucleus of mass $A = 14$–34. This radioactivity, termed cluster radioactivity, was observed for the first time in 1984 by Rose and Jones \[8\] in the decay of $^{223}$Ra. Today, 12 different clusters were observed, emitted by heavy nuclei ranging from $^{221}$Fr to $^{242}$Cm \[9\].

One- and two-proton radioactivity, as described earlier, are the two remaining decay modes observed for atomic nucleus. In the following, the studies conducted on two-proton (2p) radioactivity will be described and the results obtained will be laid out in the general context of nuclear struc-

![Diagram](image.png)

Figure 1. Chart of the nuclides with all nuclei known today plotted as a function of neutron and proton numbers. Inserts indicate the different radioactive decay modes discussed in the text and the year of discovery.
I voluntarily exclude from the discussion 2p emitters with half-lives as short as nuclear reaction times (i.e., of the order of $10^{-21}$ s). Two-proton emission from such short-lived resonances has been studied for $^6$Be, $^{12}$O, and most recently for $^{16}$Ne and $^{19}$Mg. Similarly, I do not describe 2p emission from excited states either populated by nuclear decay or by nuclear reactions. Details about these decay modes and a much more detailed discussion of experimental and theoretical aspects of 2p radioactivity may be found in Ref. [10].

Figure 1 summarizes these different decay modes indicating the year of discovery and the region in the chart of nuclei where these decays occur.

Search and Discovery of Two-Proton Radioactivity

Radioactive nuclei not existing on Earth may be produced by either fusing two stable nuclei to form a heavier nuclide or by fragmenting or fissioning heavier nuclei to produce lighter ones. The advent of projectile fragmentation [11] around 1980 allowed the production of the most proton- and neutron-rich nuclei in significant amounts. After the completion of heavy-ion fragment separators like LISE at GANIL [12], the search for two-proton radioactivity of medium-mass nuclei, for which the Coulomb barrier should create a measurably long half-life for 2p emission, began. Nuclei like $^{22}$Si, $^{31}$Ar, $^{35}$Ca, $^{38}$Ti, $^{42}$Cr, $^{45}$Fe or $^{49,48}$Ni [13] were expected to be promising candidates for this decay mode. However, although a rather small 2p branch could not be excluded for most of them, the less exotic nuclei were all observed to decay by $\beta$-delayed decays like $\beta p$ and $\beta 2p$ emission [14]. Therefore, the observation of 2p radioactivity had to await the production and identification of the most proton-rich nuclei $^{45}$Fe and $^{54}$Zn.

Two-proton radioactivity was observed for the first time in experiments studying the decay of $^{45}$Fe at GANIL [15] and at GSI [16]. The nucleus of interest was produced by projectile fragmentation of a stable $^{58}$Ni beam, selected by a fragment separator and implanted in a stack of silicon detectors, which were used to identify the fragments transmitted to the focal plane of the separator on an event-by-event basis and to detect their decays. Due to the thickness of the detectors, these experimental set-ups did not allow one to observe the two protons directly, but only (i) their sum energy as well as the shape of this sum peak, which allows one to some extent to distinguish a 2p peak from a $\beta$-delayed charged-particle decay, (ii) the decay time, which can be linked to the decay energy via theoretical models, (iii) the absence of $\beta$ radiation, which could be excluded with a high level of confidence thus excluding $\beta$ decay as the observed decay mode, and (iv) the subsequent decay of the daughter nucleus of $^{45}$Fe.

These latter data were in agreement with the known decay of $^{43}$Cr. Although none of these individual observables alone is sufficient to conclude on the observation of

Figure 2. Left-hand side: Decay energy data from all experiments [15–17] carried out with silicon detectors for $^{45}$Fe. A peak energy of $(1.151 \pm 0.015)$ MeV is determined. Right-hand side: The experimental daughter decay half-life determined by means of a gate on the 1.151 MeV peak is compared with all decay half-lives for the possible daughters ranging from $^{40}$Ti to $^{45}$Cr. Only for the 2p daughter $^{43}$Cr, the half-life agrees with the experimentally determined daughter half-life.

Figure 3. As for Figure 2, but in the case of $^{54}$Zn. The experimental data are from Ref. [18]. Although not as convincing as in the case of $^{45}$Fe, the daughter decay half-life leaves only 2p, $\beta p$, and maybe $\beta 2p$ decay as possible decay modes, the latter two being excluded by other means.
2p radioactivity, all these pieces of evidence together allow only one conclusion: the discovery of two-proton radioactivity.

Figure 2 shows the data today available for the decay energy of $^{45}$Fe, which originate from the original work [15,16] and a more recent experiment [17]. The half-life of the daughter decay gated by the observation of a first decay event with a decay energy around 1.15 MeV is shown in the same figure and compared to the half-lives of all possible daughter nuclei. Only the half-life of $^{43}$Cr is in agreement with the observed daughter decay half-life, yielding thus an independent and irrefutable argument for the observation of 2p radioactivity.

Later work performed at the LISE3 separator of GANIL could clearly identify a second ($^{54}$Zn) and maybe even a third 2p emitter ($^{48}$Ni). The results for $^{54}$Zn [18] are shown in Figure 3. The detection set-up was identical to the one used for the decay study of $^{45}$Fe at GANIL. Therefore, the

![Graphs showing 2p radioactivity data and predictions](image)

**Figure 4.** Comparison of the experimental data for two-proton radioactivity with the predictions of three models described in the text. When plotting the partial 2p decay width or the partial 2p half-life as a function of the 2p decay energy, nice agreement experimental data and theory for $^{45}$Fe, $^{48}$Ni, and $^{54}$Zn is obtained, giving thus also some confidence that the observed $^{48}$Ni decay event is indeed due to 2p radioactivity.
same chain of arguments was used. In a similar way, although with less precision, the daughter decay could be used to demonstrate that 2p radioactivity was observed also for this nucleus.

For $^{48}$Ni, the situation is less clear. Although four $^{48}$Ni nuclei were observed [17], only one of the decay events has all the characteristics of 2p radioactivity. The other decay events were $\beta$-delayed decays, the competitor decay mode. Therefore, two-proton radioactivity for $^{48}$Ni needs further confirmation.

**Comparison to Theoretical Models**

Already before the observation of two-proton radioactivity, theoretical models were developed to describe 2p radioactivity. These models treat at different levels of sophistication the nuclear structure of the nuclei involved and the dynamics of the emission process. The first model to be proposed is an approach based on the rather old R-matrix model [19] originally developed to describe proton capture of nuclei. This model was first applied for the time reversed process, the emission of one proton, and then extended to the emission of two protons. In its first version, 2p emission was simplified through the emission of a diproton, a structure-less object consisting of two protons without any internal structure. Recently, this approach was developed into a model that takes the proton-proton resonance into account [20]. This model treats the nuclear structure in a rather sophisticated manner, but it does not include the emission dynamics. Nonetheless, it yields good agreement with the experimental data (see Figure 4).

A model that treats the emission dynamics on reasonable grounds is the three-body model of Grigorenko et al. [21]. This approach uses realistic proton-proton and proton-core interactions and can therefore, beyond the relation between the decay energy and the decay time, also determine the angular distribution and the energy sharing of the two protons. However, nuclear structure is treated only at the level of single particle levels and a mixing of them. Even with this deficiency, the three-body model is today the model that allows the most detailed comparison between experimental data and theoretical predictions.

The latest model developed is the shell model embedded in the continuum (SMEC). The model couples the well-known shell model of the atomic nucleus with the continuum of unbound levels. After the proposal of this model with one particle in the continuum, it was recently extended to two particles in the continuum in order to describe two-proton radioactivity [22]. From a nuclear structure point of view, this model is certainly the most complete of the three approaches. However, the emission dynamics is not treated in this model. The results obtained within the model are also shown in Figure 4.

**Direct Observation of Two-Proton Radioactivity**

As discussed earlier, the experiments performed with silicon telescopes did not allow the direct observation of the two protons. The emitter nuclei are deeply implanted in a silicon detector and the range of the protons is too short for them to escape from the detector. Thus only their total

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Figure 5. Schematic representation of the two extreme pictures of 2p radioactivity: Uncorrelated decay (left) and $^2$He decay (right). Both are rather schematic views of 2p radioactivity. A more realistic picture as in the three-body model of Grigorenko et al. yields a more complicated correlation behavior than these simple pictures. (Figures courtesy of J. Giovannoz.)

Figure 6. Left hand side: Picture as taken with the CCD camera of the Warsaw TPC showing horizontally the faint trace of a $^{45}$Fe ion implantation and the bright trajectories of the two protons (courtesy of M. Pfützner). Right hand side: Two-proton event from $^{45}$Fe reconstructed from the ASIC information of the Bordeaux TPC.
decay energy, that is, the sum of the individual proton energies and of the daughter nucleus recoil energy, could be detected. Nonetheless, as just shown, this information allows a qualitative and quantitative comparison of experiment and theory. However, to study the decay mechanism and to distinguish between the originally proposed, rather simple and schematic decay scenarios or a more sophisticated decay mechanism, more experimental information is required.

These schematic models (see, e.g., Ref. [23]) proposed either an uncorrelated decay, that is, the decay has to satisfy only conservation laws like energy and momentum conservation and an isotropic angular distribution of the two protons is expected, or a rather strong correlation, which was named $^3$He decay, where the two protons stick together until they have tunneled through the Coulomb barrier and would thus exhibit a strong angular correlation. It was quite clear rather early that a detailed study of $2p$ radioactivity requires angular and energy distributions of the individual protons to be measured (see Figure 5). Meanwhile, the three-body model of Grigorenko et al. [21] predicted more realistic but also more complicated angular distributions and an equal sharing of the available energy between the two protons.

In order to overcome the deficiency described for the silicon detector arrays, gas detectors were developed, where the path of the protons is much longer (typically centimeters) than in silicon detectors (typically micrometers) and can in addition be visualized. Such detectors are based on the principle of time projection chambers (TPCs) where the charges created due to the energy loss of charged particles like heavy ions or protons are projected by an electric field onto a two-dimensional detection matrix. This matrix yields a 2D view of the decay event taking place in the detector. The third dimension is obtained by the time delay of the drift of the electron cloud from its creation point along the charged-particle track to the detection plane.

Such detectors were developed in Bordeaux and in Warsaw. The Bordeaux detector [24] is realized with an electronic readout based on ASIC electronics. 1,568 channels are read out for each event and allow the reconstruction of ion implantation and decay events. The Warsaw detector [25] uses a CCD camera and a photomultiplier readout via a digital oscilloscope to register the events taking place in the detector gas. Both detectors allow thus to visualize in 3D the individual tracks of the two protons.

The first experiment with such a detector was carried out at the LISE3 facility of GANIL using the Bordeaux TPC [26]. Although only a limited number of events could be observed, it could be demonstrated that indeed two protons are emitted in the decay of $^{45}$Fe. An experiment [27] carried out at the National Superconducting Cyclotron Laboratory with the Warsaw detector collected higher-statistics data. Events from both experiments are shown in Figure 6. The MSU experiment could thus show for the first time experimentally that the two protons share equally the available energy (confirmed by the GANIL data) and that the angular distribution of the two protons presents a two-hump structure, in nice agreement with the three-body model of Grigorenko et al. Figure 7 compares both data to the predictions of the three-body model. Agreement is obtained between experimental and theoretical data.

Recently, the decay of $^{52}$Zn was studied at LISE3/GANIL with the Bordeaux TPC and clear evidence was
obtained for 2p emission. These data are presently analyzed. However, as the production cross-section for $^{54}$Zn is more than two times smaller than the one for $^{45}$Fe, conclusions will be possibly biased by statistics.

Future Studies

For the moment, 2p radioactivity is a curiosity of nuclear structure rather than a tool to investigate the structure of the atomic nucleus. In order to allow detailed studies of nuclear structure and to investigate, for example, the nuclear pairing, the sequence of single particle levels or the content of the nuclear wave function of the emitted protons, more 2p emitters have to be produced and studied, with the TPC detectors, but also by means of silicon detector arrays as only these systems allow one to measure the decay energy with sufficient precision. Gas detectors like TPCs are not able to yield precisions that make a comparison with models reasonable as far as the decay energy is concerned.

Future studies will therefore try to discover 2p radioactivity for nuclei like $^{59}$Ge, $^{63}$Se, and $^{67}$Kr, but also to confirm the results for $^{40}$Ni. Once two-proton radioactivity has been established for these isotopes by means of silicon detector arrays and the decay half-life, the branching ratio and the total decay energy have been measured with sufficient precision, they will be investigated by means of TPC detectors in order to study the proton-proton correlations in 2p decay of these nuclei as it was done for $^{45}$Fe and $^{54}$Zn.

In parallel, the nuclear models have to be refined. In particular, nuclear structure aspects and nuclear dynamics should be treated at the same footing. However, this is certainly not a trivial enterprise.

References

The n_TOF Facility at CERN: A New Approach to Quests in Astrophysics and Technology

Neutrons have always been produced by spallation reactions with the high energy beams hitting various targets at CERN, but it was not before 2000 that neutrons were produced on purpose for experiments related to problems in nuclear astrophysics and technology. Initiated by Carlo Rubbia and his colleagues [1] and supported as a European project [2] the construction of n_TOF facility started in 2000. In parallel, the n_TOF Collaboration was established with about 120 participants from more than 30 institutes, mostly from the EU, but also from the United States and Russia, to build the experimental equipment for neutron cross-section measurements and to prepare the first measurement campaign from 2002 to 2004. The main goal of the n_TOF project was “to produce, evaluate and disseminate cost-effectively neutron induced reaction cross-sections for isotopes relevant to the Stellar Nucleosynthesis, to Nuclear Physics and to the concept for an Accelerator Driven System. In total, 40 fission and capture cross-sections in the mass range between $^{24}$Mg and $^{245}$Cm have been successfully measured during the first campaign. Presently, the n_TOF Collaboration is preparing for the second campaign 2009–2012 after the facility was refurbished and after a new spallation target has been installed.

The n_TOF Facility

At n_TOF, neutrons are generated by spallation reactions induced by a pulsed 20 GeV proton beam from the proton synchrotron complex in a Pb target block (Figure 1). The neutrons are slowed down in the lead and moderated in the surrounding 5 cm thick layer of cooling water. The schematic sketch of the facility in Figure 1 shows the position of the various elements along the evacuated neutron flight path in the 200 m long n_TOF tunnel. Starting from the spallation target the neutron beam passes heavy concrete and iron shieldings, the sweeping magnet at 145 m, and two collimators at 135 and 175 m, before it arrives at the measuring station 185 m downstream of the lead target. The characteristic parameters of the n_TOF facility are summarized in Table 1 (for details see Refs. [3,4]).

The n_TOF facility is characterized by the combination of high neutron flux, excellent time resolution, and very low backgrounds. What is unique, however, is the outstanding duty cycle of only one intense proton pulse every 2.4 seconds, which makes n_TOF the most luminous neutron source worldwide. These features are providing the ideal environment for neutron time-of-flight (TOF) experiments covering a wide energy range from thermal to about 250 MeV (higher energy neutrons are produced as well, but they have not been effectively used for measurements so far). The excellent performance of the facility is complemented by the use of the most advanced detection and data acquisition techniques for neutron cross-section studies (n_TOF Ref. 1), thus offering exciting experimental opportunities for applications in nuclear astrophysics and for advanced nuclear technologies.

Nuclear Astrophysics: The Quest for the Origin of the Heavy Elements

The first three chemical elements found in Nature have been produced during the initial few minutes of life of the Universe: hydrogen, helium, and a tiny amount of lithium are the only products of the Big Bang nucleosynthesis. All the other elements (Z > 3) are synthesized in stars and in stellar explosions. The quest for understanding the origin of the natural elements is therefore strongly connected to the understanding of the mechanisms of life and evolution of stars and, as we shall see, to the nuclear reaction processes taking place in the interiors of stars.

Stellar Scenarios

The power balance of stars is provided by the fusion of charged particles, which leads stepwise to the production of the abundances between He and Fe. Beyond Fe, fusion reactions are impeded because there is no energy gain due to the decreasing binding energies and because the Coulomb barriers are becoming too high at the available temperatures in the stellar interior. Hence, further build-up of heavier elements is taken over by neutron capture [5] (Figure 2).

There are two neutron capture processes, each contributing about half of the abundances beyond Fe, which are named according to their characteristic time scales. The slow neutron capture process ($s$ process) takes place during the He burning
stages of stellar evolution, when stars are becoming Red Giants. In low mass stars, neutrons are produced alternatively by \((\alpha, n)\) reactions on \(^{13}\text{C}\) and \(^{22}\text{Ne}\) at temperatures of 90 and 280 MK, corresponding to thermal energies of \(kT = 8\) and 23 keV. These stars are producing the so-called main \(s\)-process component, which is responsible for the \(s\) abundances in the mass region from Zr to Bi \([6,7]\). The \(s\) process in massive stars, which are producing the weak component between Fe and Sr, operates partly during core He burning at \(kT = 26\) keV and partly during shell C burning at \(kT = 90\) keV \([8]\). Because the neutron capture times in the \(s\) process are much longer than typical half-lives for beta decay, the reaction path follows the valley of stability and involves mostly stable isotopes.

The second mechanism is the rapid neutron capture process \((r\) process\) that is commonly associated with supernova explosions. In this case, neutron densities are extremely high, resulting in neutron capture times in the range of milliseconds or less, much faster than beta decays. Accordingly, the \(r\)-process path runs close to the neutron drip-line and comprises a complex reaction network among exotic and extremely neutron-rich isotopes.

The relevant nuclear physics input for the \(s\) and \(r\) processes is determined by the time scales: in the \(s\) process the resulting abundances are governed by the neutron capture cross-sections of the stable nuclei in the stability valley, whereas the \(r\) abundances depend on the unknown beta decay rates on the \(r\)-process path as well as on the decay chains back to stability after the explosion. Obviously, the nuclear input for the \(s\) process can be accurately

Figure 1. Layout of the \textit{n}_TOF facility at CERN (a). The neutron beam line in the \textit{n}_TOF tunnel (b).
determined in laboratory experiments, whereas the situation for the r process remains very uncertain to date. Only with the relatively recent development of radioactive beam facilities, experimental nuclear physics could begin to investigate those “exotic” regions, domain of the r process.

Under stellar conditions, neutrons are quickly thermalized in the hot and dense stellar plasma, leading to Maxwell-Boltzmann spectra in the range between $kT = 8$ and 90 keV, depending on the particular site. The effective Maxwellian averaged cross-sections (MACS) are obtained by folding the energy-dependent neutron capture cross-section $\sigma(E_n)$ with the thermal spectrum. This defines the energy range from 100 eV to well above 500 keV, which has to be covered in the cross-section measurements, and where n_TOF offers excellent opportunities. This is particularly true even for unstable isotopes, which are crucial for the analysis of branchings in the reaction path of the s process as demonstrated in the example of $^{151}\text{Sm}$ below.

### Branchings in the s Process: Probes for the Stellar Interior

The unstable isotope $^{151}\text{Sm}$ represents one of the branching points in the neutron capture flow. The branching at $A = 151$ (Figure 3) is defined by the abundances of $^{152}\text{Gd}$ and $^{154}\text{Gd}$, which are considered to be of pure s-process origin, because they are shielded from possible r-process contributions by their stable Sm isobars. The partition of the neutron capture chain reflects the competing neutron captures and beta-decays at the unstable branching points $^{151}\text{Sm}$ and $^{154}\text{Eu}$. The relevant neutron capture and beta-decay rates are determined by the neutron density and temperature at the site of the s process. Under stellar conditions, the beta-decay rates of both branching points are significantly higher compared to their terrestrial values due to the population of low-lying states by the intense stellar photon bath, a feature that allows one to interpret this branching as an s-process thermometer.

The strength of the branching at $^{151}\text{Sm}$ is defined by the competition between neutron capture and beta decay. Knowing the neutron capture cross-section from the n_TOF experiment, the stellar beta decay rate can be tuned to reproduce the abundance of the s-only isotope $^{152}\text{Gd}$. In this way, the stellar temperature at the s-process site can be inferred from the temperature dependence of the half life of $^{151}\text{Sm}$.

From the measured cross-section, $\sigma(E_n)$, Maxwellian averaged cross-sections were determined for the relevant range of thermal energies between 5 and 30 keV. Figure 5 shows a comparison between the present value of $3100 \pm 160$ for $kT = 30$ keV with previous predictions based on statistical model calculations. In this case all titanium can with 0.2 mm thick walls. Events were registered via the prompt capture gamma-ray cascade using two liquid scintillation detectors close to the neutron beam line. Figure 4 illustrates the measured capture yield from the samarium sample compared to the background obtained with an empty can and a can containing graphite to simulate the effect of sample scattered neutrons. The data show good counting statistics over the entire neutron energy range from 0.1 eV to 1 MeV with very good signal to background ratios. Note, that the data are plotted on a much coarser energy grid than recorded. The actual resolution was good enough for resolving single resonances up to 1 keV in spite of the high-level density of $^{151}\text{Sm}$.

![Figure 2. Solar system elemental abundances.](image-url)
theoretical results are smaller than the experimental value, in contrast to the neighboring branching point $^{147}\text{Pm}$, where the cross-section was always overestimated. After a crucial uncertainty in the analysis of $^{151}\text{Sm}$ branching could be removed by the cross-section measurement, it was found that 71% of the solar abundance of $^{152}\text{Gd}$ could be reproduced by the stellar model for the main component of the $s$ process [7]. The missing part of the $^{152}\text{Gd}$ abundance matches the expected contribution by the $p$ process if compared with the abundances of the nearest $p$-only isotopes $^{156}\text{Dy}$ and $^{158}\text{Dy}$. The successful reproduction of the abundance pattern in the $^{151}\text{Sm}$ branching suggests that neutron flux and temperature history of the stellar $s$ process are consistently described with the stellar model for the Red Giant phase of low mass stars, a sensitive test that needs to be confirmed by similar analyses for a number of other branchings.

**More Astrophysics**

Additional $s$-process-related measurements at n_TOF were motivated by isotopic anomalies in presolar dust grains (Mg, Zr) by the use of La as an $s$-process indicator in astronomical observations, by the interpretation of the $^{187}\text{Re}/^{187}\text{Os}$ pair as a cosmochronometer, and by the abundance pattern in the Pb/Bi region for studying the termination of the $s$-process path and the related recycling by $\alpha$-decays from Po. The respective publications are listed at the end of the article and can be found on the n_TOF website (http://www.cern.ch/ntof).

**Cross-Sections for Applications in Technology**

The strategies foreseen for future employment and development of nuclear power generation underline the use of nuclear energy systems in which the nuclear fuel contains consistent amounts of the minor actinides (MA). These minor actinides, particularly neptunium and americium, are produced as normal by-products of the operation of thermal power reactors. Because of the existence of long-lived isotopes of these elements, they constitute the major sources of the residual radiation in spent fuel and in wastes resulting from reprocessing. Therefore, it is mandatory to gain availability of reliable and accurate neutron-induced reaction cross-section data for the important isotopes of the MA elements. Relatively low uncertainties in these data are required for core design studies, as well as for high burn-up strategies.

Most of the experimental neutron cross-section data are available for the main uranium and plutonium isotopes, reflecting the past and current interest in the U/Pu fuel cycle at neutron energies ranging from thermal to fast, as required for thermal and fast reactors. Although the existing nuclear databases could be sufficient for a first evaluation of critical reactors as well as for ADS (Accelerator Driven Systems), a detailed assessment of important integral reactor quantities requires precise and complete sets of basic nuclear data, including the most important isotopes of the MA elements. A second aspect of the importance of nuclear data for advanced nuclear technologies that has been addressed in the activities of the n_TOF Collaboration has been that of the Th/U nuclear fuel cycle. The use of thorium in the nuclear fuel cycle for either critical or subcritical systems is now a topic of great interest. This cycle is based on the fertile $^{232}\text{Th}$ and the fissile $^{233}\text{U}$, formed by neutron capture on $^{232}\text{Th}$ and the subsequent $\beta$ decays of $^{233}\text{Th}$ and $^{233}\text{Pa}$. An interesting advantage in using this fuel cycle, as compared to the conventional
facilities and methods

uranium/plutonium cycle currently used in all operating power plants, is related to its low production of high-mass actinides, including plutonium, making it appealing for the reduced proliferation capabilities.

Just to give a flavor of the measurements performed at n_TOF and mostly motivated by the important implications for advanced nuclear technologies, we show the example of the $^{232}$Th(n,$\gamma$) cross-section measurement (Figure 6). The uncertainty on this important quantity has been reduced down to 4% in the fast energy region, demonstrating the high accuracy reachable with the experimental set-up used (see n_TOF Ref. 3 for details).

A partial list of other measurements performed at n_TOF for advanced nuclear technologies as main field of applications includes capture cross-section measurements on $^{237}$Np, $^{240}$Pu, and $^{243}$Am (all performed with the n_TOF total absorption calorimeter, Figure 7), as well as fission cross-section measurements on $^{233,234}$U, $^{237}$Np, $^{241,242}$Am, and $^{245}$Cm. An example illustrating the sensitivity achieved in (n, 2) measurements on radioactive samples is shown in Figure 8.

Plans for the Future

The 200 m flight path of the present n_TOF facility is of great advantage for measurements with high resolution in neutron energy. However, the overall efficiency of the experimental program and the range of possible measurements could be enormously improved with the installation of an additional shorter flight path of approximately 20 m. There are two main reasons for this improvement.

The existing flight path is positioned at an angle of only 10 degrees with respect to the incident proton beam line. Therefore, a burst of weakly interacting relativistic spallation products is emitted into the neutron flight path at each proton pulse. In spite of massive shieldings and the use of a sweeping magnet for deflecting the charged particles, a remaining background in the form of a “time-zero flash” is causing an overload of the detectors and hampers measurements at high neutron energies. In particular, capture measurements with the total absorption BaF$_2$ calorimeter, fission studies with ionization chambers, and measurements with Ge detectors, for example, of (n,xn) cross-sections, are strongly affected by this flash. Because all particles causing the flash are emitted in a forward direction the flash would be strongly reduced at an angle of 90 degrees with respect to the proton beam direction.

The second main motivation for the implementation of a second beam line is related to the possibility of obtaining a much higher neutron flux (a factor of roughly 100) with respect to the present neutron fluence in

![Figure 6. Neutron capture cross-section of $^{232}$Th. The measurement has been performed in the full energy range, but only the fast region is shown here.](image)
EAR-1 set at 200 m from the spallation module.

The example of the $^{151}$Sm branching needs to be complemented by the investigation of a variety of branchings, which exhibit different sensitivities with respect to the physical properties of the $s$-process scenarios such as neutron density, pressure, convection, and mixing effects or for defining time scales from minutes to the age of the Universe. The use of these cases as probes for the stellar interior and as tests for models of stellar evolution depends crucially on the quality of the cross-section data for the involved isotopes. While these objectives will continue to play a major role for the n_TOF program, the key objective for the near future are the capture cross-section of all stable Fe and Ni isotopes, which are of crucial importance as seed nuclei for the $s$ process in general and for the abundances of the weak component in particular, because they are affecting the overall $s$-process efficiency up to mass number $A \approx 90$. With the exciting prospects of the shorter flight discussed before, more unstable isotopes will be in reach of the n_TOF experiments with appealing opportunities for refined branching analyses.

For measurements on actinide isotopes, there would be practically no more serious limitations due to the radiotoxicity of the sample. For instance, the necessary amount of $^{241}$Am could be limited to 10 micrograms corresponding to an activity of 106 Bq only. Even cross-section measurements at yet shorter-lived actinide isotopes would be possible at such a short flight path (e.g., on $^{238}$Pu, $^{242}$Am, and $^{242,243,244}$Cm).

Also in the field of nuclear fission the high flux and still superb TOF resolution will allow one to perform much more comprehensive measurements covering the many facets of this complex reaction in a more adequate way.

In summary, an additional, short flight path at n_TOF bears most exciting options for a completely new class of experiments and will

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**Figure 7.** The n_TOF total absorption calorimeter (TAC), an array of BaF2 detectors for capture cross-section measurements.

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**Figure 8.** Measurement of the $^{240}$Pu(n,$\gamma$) performed with the total absorption calorimeter (TAC).
be further investigated by detailed simulations and by studying the technical feasibility. Meanwhile, excellent quality of measurements at n_TOF will continue to provide results that can be considered as milestones in terms of accuracy and consistency.

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Polarized Radioactive Beams and Nuclear Moment Measurements for Exotic Nuclei

Introduction

Viewing a nucleus as a collection of independent particles has been, since the spin-orbit force was introduced [1], a successful way of understanding major nuclear properties that are governed by a particular series of numbers—the magic numbers. Such properties result from the bunching of the single-particle orbits, or the existence of nuclear shells. About half a century after, however, the present-day studies of nuclei far from the β stability line reveal that the nuclear shells may evolve [2]: As the ratio increases, the single particle orbits migrate upward or downward in energy depending on their $j = l ± 1/2$ character. As a result the decisive role played by one orbit (the valence orbit) is diminished, whereas another orbit (the spectator orbit) takes over by another, and in some cases the nuclear deformation sets in even in a nucleus whose $N$ or $Z$ number is a (heretofore) magic number. In such a situation, the nuclear moments, namely the magnetic dipole moments $μ$ and electric quadrupole moments $Q$, serve as very useful indicators for alterations in nuclear structure.

In the region of exotic nuclei, however, the measurement of $μ$ or $Q$ is a nontrivial task, because such a measurement requires certainly high production yields of the objective nucleus and, moreover, the polarization or alignment of its spin. A breakthrough was gained in an experiment conducted by a RIKEN–GANIL–Orsay collaboration [3] at the LISE spectrometer at GANIL, which revealed that the projectile fragmentation (PF) reaction at intermediate energies is capable of producing spin-aligned exotic nuclei. A subsequent experiment at RIKEN revealed that the PF reaction also provides significant spin polarization [4]. After several experiments investigating the mechanism and properties of the polarization/alignment [5–7] were conducted, a series of experiments to study static nuclear moments for exotic nuclei was initiated. This article reviews results of those experiments performed until now with polarized/aligned projectile fragments.

Spin Polarization in Projectile Fragmentation

Results of the spin alignment measurement [3] are presented in Figure 1(a) for a fragment $^{14}$B from the fragmentation of a projectile $^{18}$O on a Be target at $E/A = 60$ MeV/u. The alignment, $A = (2a_{+2} - a_{+1} - 2a_{0} - a_{-1} + 2a_{-2})/2$ where $a_m$ denotes the population probability for the sublevel $m$ of $^{14}$B spin $I = 2$, observed for fragments in a narrow momentum region ($Δp/p = 2$ %) around the peak of the yield is positive, whereas $A$ becomes negative when averaged over a wider region ($Δp/p = 4$ %) around the peak. In a high momentum tail it takes a large negative value. The polarization, $P = a_{+1} - a_{-1}$ for the $I = 1$ case, is presented in Figure 1(b) for a $^{15}$B fragment ($I = 1$) from the fragmentation of a $^{19}$N projectile (40.6 MeV/u) on an $^{197}$Au target [4]. $P$ is negative in the low-momentum tail, crosses zero at the peak, and increases to large positive values in the high-momentum tail.

The observed behaviors of $A(p)$ and $P(p)$ as functions of the fragment momentum $p$ are explained by a simple kinematical argument concerning the PF process, as follows. In a model of the PF reaction, nucleons (the participants) in the overlapping part of the projectile nucleus are removed without altering the momenta of the remaining nucleons (spectators). The momentum $p$ of the projectile fragment (a cluster of the spectator nucleons) is thus written as $p = Mv_0 - q$ where $v_0$ denotes the projectile velocity in the laboratory frame and $q$ the sum momentum of the removed nucleons (participants) in the projectile-rest frame. $M$ is the mass of the fragment. The participants also carries away the orbital angular momentum $R \times q$ where $R$ denotes the average position of the participant nucleons at the moment of removal, measured from the center of the projectile. Thus, the fragment spin $J$ (assuming that the projectile had no spin, for simplicity) is related to $p$, as $J = -R \times q = R \times (p - Mv_0)$, as illustrated in Figure 1(c).

It may be interesting to put the aforementioned argument in a quantal form (although too much simplified) by writing the cross-section for the PF process where one nucleon having an internal momentum $q_s$ is removed from the projectile based on the multiple scattering theory [8], as

$$\sigma_{\text{m}}(q_s) = \int d^2 s D(s) \int dz \int d^2 q \rho_m(x; q)$$  \hspace{1cm} (1)$$

Here $x = (s, z)$ and $q = (q_x, q_z)$, respectively, denote the position and momentum of the nucleon in the projectile nucleus that is to be removed. $W_m(x; q)$ is the Wigner transform of the one-body density matrix $\langle x_1 | \rho_m | x_2 \rangle$, and represents (in a restricted sense) the momentum distribution of the nucleon in the projectile.
The yield \( s(p_z) \) and the spin polarization \( P(p_z) \) of the fragment is given by
\[
s(p_z) \equiv s - 1 + s_0 + s_1 + s_2 - 1 \mu \left[ (a R)^2 + \frac{q_z}{a} \right] \exp\left[-\frac{q_z}{a} \right] (4)
\]
and
\[
P(p_z) = \frac{\sigma_{-1} - \sigma_{+1}}{\sigma} = -\frac{Rq_z}{(a R)^2 + (q_z/a)^2} (5)
\]
where \( q_z = Mq_0 - p_z \). Here the nucleon removal is assumed to occur from the \( 0p \) orbit of the harmonic oscillator potential with a constant \( 1/a = \sqrt{\hbar/m_0} = 1.75 \) fm. The result is also illustrated in Figure 1(c).

In the developmental studies that followed [5,6] it turned out that the spin polarization of fragment occurs quite generally, for different projectiles, targets, fragment nuclei, and projectile energies in a level of 2–10% in size, as shown in Figure 1(d)–(h). The momentum dependence of polarization was found reversed when a light-mass target or a higher-energy projectile is employed so that the collision is considered to proceed the far-side trajectory. With a medium weight target at the projectile energy of 110 MeV/u, an intermediate case occurs where the polarization takes a maximum at the peak momentum. This behavior was explained as an effect of rescattering of the removed nucleons [6]. The spin alignment at a higher projectile energy 500 MeV/u was observed [7] by using a fragment separator FRS at GSI. The time-differential perturbed angular distribution (TDPAD) pattern \( R(t) \) representing the spin rotation was observed for a \( ^{43}\text{m} \text{Sc} \) \((P = 19/2^+, T_{1/2} = 473 \text{ ns}) \) isomer from the fragmentation of 500 MeV/u \( ^{46}\text{Ti} \) projectiles. The observed amplitude of \( R(t) \) indicates that the \( ^{43}\text{m} \text{Sc} \) isomer produced in the center of the momentum distribution is spin aligned to about +35%, suggesting that the projectile fragmentation reaction is useful also for isomer studies with TDPAD technique.

**Nuclear Moments in the Region Far from the \( \beta \)-Stability**

Spin-polarized radioactive nuclear beams produced with the method presented earlier have been utilized for the nuclear moment measurements with the \( \beta \)-NMR technique. In Figure 2, species whose magnetic moment or quadrupole moment was determined with this technique at RIKEN are indicated on the nuclear chart. I pick up some of them below to show how the moment measurements are related to nuclear structures in the regions far from the stability line.

**Nuclear-Moment Signals for Large-N/Z Effects**

The magnetic moment for the ground state of \( ^{14}\text{B} \) was determined [9] to be \( |\mu(\text{^{14}B})| = 1.185 \pm 0.005 \mu_0 \). With three protons in the \( p \) shell and one neutron in the \( sd \) shell, the \( J^p = 2^- \) ground state of \(^{14}\text{B} \) should be dominated by two configurations, \(|\text{p}_{1/2} \otimes \text{s}_{1/2} \rangle^J = 2_2^+ \) and \(|\text{p}_{3/2} \otimes \text{d}_{5/2} \rangle^J = 2_2^+ \). To leading order, therefore, the magnetic moment of \(^{14}\text{B} \) is given by a weighted average of the moments \( \mu_1 \) and \( \mu_2 \) for these two configurations (note that the off-diagonal matrix element of M1 operator between these configurations vanishes), as
\[
\mu(\text{^{14}B}) = \frac{|c_1|^2 \mu_1 + |c_2|^2 \mu_2}{(|c_1|^2 + |c_2|^2)}. (5)
\]
with weights being the probabilities $|c_i|^2$ and $|c_j|^2$ for the respective configurations. Because $\mu_1$ and $\mu_2$ are quite different from each other ($\mu_1 = + 1.88 \mu_N$ for the former and $\mu_2 = - 0.98 \mu_N$ for the latter, evaluated with the effective M1 operator used in literature [10]), the measurement of $\mu$ provides a sensitive measure for the relative importance between these configurations. This statement remains unaltered even counting that Eq. (1) holds only approximately (the configurations 1 and 2 together share 87% of the $^{14}$B ground state in shell-model calculations with PSDMK interactions for example, with remaining 13% probability being shared by many other minor configurations). The measured $\mu$, however, turned out to be substantially larger than the calculation with single-particle energies normally adopted for the $s_{1/2}$ and $p_{1/2}$ orbits [11], indicating that the ground state of $^{14}$B contains more $|\psi(p_{1/2})\rangle \otimes \psi(d_{5/2})$ component than usually considered. The enhanced contribution of configuration 1 relative to configuration 2 should occur either if the single-particle energy $\varepsilon_{s_{1/2}}$ for the $s_{1/2}$ orbit is lower than usual, or if $\varepsilon_{d_{5/2}}$ for the $d_{5/2}$ orbit is higher. In fact, good agreement between the calculation and experiment was obtained when the difference $\Delta \varepsilon = \varepsilon_{d_{5/2}} - \varepsilon_{s_{1/2}}$ are reduced by about 1 MeV from the value normally employed in the region of the $\beta$ stability. The reduced $\Delta \varepsilon$ in the neutron-rich nucleus $^{14}$B was also inferred from the position of the experimentally found 1$^+$ state in a $\beta^-$ delayed-neutron-$\gamma$ spectroscopic experiment [12]. Systematic lowering of the $s_{1/2}$ orbit single-particle energy has been discussed in literature since long before [13].

The case of $^{17}$N, with spin-parity $1/2^-$, is also interesting because its nucleon configuration is defined quite sharply [14]. With one proton hole in the $p$ shell and two neutrons in the $d_{5/2} - s_{1/2}$ shell, this nucleus is allowed to contain only two configurations, $\psi_0 = |\psi(p_{1/2})\rangle \otimes |d_{5/2} s_{1/2}\rangle$ and $\psi_2 = |\psi(p_{1/2})\rangle \otimes |d_{5/2} s_{1/2}\rangle$ (note that two neutrons within the $d_{5/2}$ and $s_{1/2}$ orbits cannot form $J_n = 1$ because of the symmetry). Of the two configurations, of course $\psi_0$ should dominate because of the $J_n = 0$ preference to $J_n = 2$ on the neutron side. In the magnetic moment, however, the contribution of $\psi_2$ will be magnified because the $\mu$ of $\psi_2$ is an order of magnitude larger than the $\mu$ of $\psi_0$ [in both configurations $\mu$ is carried essentially by proton, with $\mu_{p,N}(p_{1/2}) = + 3.80 \mu_N$ and $\mu_{p,N}(d_{5/2}) = - 0.276 \mu_N$]. The measured result for $\mu(^{17}$N) = 0.3526 ± 0.0026 $\mu_N$ was substantially larger than $|\mu_{p,N}(p_{1/2})|$, and was attributed to the contribution of $J_n = 2$ coupling through shell-model calculations. The experimental $\mu(^{17}$N) was explained by assuming that the $J_n = 0$ pairing energy for neutrons, of which an extensive part comes from core-polarization effect [15], is weakened by 30% in this neutron-rich nucleus. The magnetic moments, low-lying levels, and binding energies of $^{17}$B and $^{15}$B also are explained with the hypothesis that the $J_n = 0$ pairing is weakened for neutrons by about 30% [9,14].

The electric quadrupole moment is written as

$$Q = \langle I,M = +|\Sigma_k \langle \mathbf{Q}_k | M = +| \rangle, \quad (6)$$

with $\mathbf{Q}_k \equiv \sqrt{16 \pi / 3} r_k^3 Y_{20}(i_k)$ and the electrical charge $e_k$ for the $k$-th nucleon. Looking at this expression naively, it might appear that $Q$ receives no contribution from neutrons. As a matter of fact, however, we need to adopt in Eq. (2) a model wave function $|\psi_{I,M = +1}\rangle$ in place of the true nuclear state $|I,M = +1\rangle$, and as a result we should take into consideration that the valence
neutrons polarize the core protons, incorporating the configurations outside the model space. In such a case, \( e_p \) need to be replaced by effective charges \( e_p^{\text{eff}} = e + \delta e_p \) for proton and \( e_n^{\text{eff}} = e + \delta e_n \) for neutron. Empirically the E2 polarization charges are known to take values \( \delta e_n = 0.5e \) and \( \delta e_p = 0.3e \) in light-mass nuclei close to the \( \beta \) stability [16]. \( \delta e \) would be smaller than these, if the coupling of the valence nucleon with core is weaker than usual. The measured \( Q \) for \( ^{15}\text{B} \) and \( ^{17}\text{B} \) are found [17,18] to be very close to \( Q \) of the neutron-closed isotope \( ^{13}\text{B} \), indicating that \( e_n^{\text{eff}} \) is quenched in \( ^{15}\text{B} \) and \( ^{17}\text{B} \). Small experimental \( Q \) obtained for \( ^{18}\text{N} \) \( (Q \) of this nucleus is predominated by the neutron side because of a \( p_{1/2} \) hole character of the proton side) indicates that \( e_n \) is significantly reduced also in this nucleus [19]. These results on \( Q \)-moments clearly demonstrate that the E2 effective charges are isospin-dependent. This has already been pointed out by the textbook of Bohr and Mottelson [20] considering the decoupling feature of loosely bound particles as well as modification of the high-frequency isoscalar and isovector quadrupole modes [18,21]. The reduced effective charge for neutron in a neutron-rich nucleus is also compatible with recent observation of hindered E2 transitions [22] from the first \( 2^+ \) excited states in \( ^{16,18}\text{C} \).

**Spin Assignments**

The ground-state spin-parity of \( ^{17}\text{C} \) has been discussed from several theoretical and experimental approaches. According to shell model calculations, \( I^\pi = 1/2^+, 3/2^+ \) and \( 5/2^+ \) are candidates for the ground state, but narrowing down to one from them based on theory is very difficult because the calculated energies for these three low-lying states are very close to each other. Experimentally, from the \( \beta \)-decay branching ratio, the \( I^\pi = 5/2^+ \) spin-parity assignment is excluded. Of the remaining candidates \( I^\pi = 1/2^+ \) and \( 3/2^+ \), the latter has been proposed from the \( \beta \)-delayed neutron spectroscopy and one-neutron removal reactions. Under such a circumstance, the measurement of the \( g \)-factor plays a decisive role because it is extremely sensitive to whether the spin-parity is \( 1/2^+ \) or \( 3/2^+ \). The \( g \)-factor of the \( ^{17}\text{C} \) ground state was measured to be \( |g_{(1/2^+)}| = 0.5054 \pm 0.0025 \) [23]. The experimental \( |g| \) is well reproduced by both calculations with the PSDMK and PSDWBT interactions for spin-parity \( 3/2^+ \), while the calculated \( |g| \)'s for \( I^\pi = 1/2^+ \) are about 6 times larger. Thus, the ground-state spin-parity of \( ^{17}\text{C} \) was assigned to be \( I^\pi = 3/2^+ \), and the possibility of \( I^\pi = 1/2^+ \) was clearly excluded.

A new method of spin-parity assignment was developed that makes use of \( \beta \)-ray asymmetry measured in coincidence with delayed neutron in the \( \beta \) decay of a spin-polarized parent nucleus. Neutron-emitting excited states of \( ^{15}\text{C} \) that was fed through the \( \beta \) decay of \( ^{15}\text{B} \) were studied [24]. This technique has been utilized later in the study of excited states of \( ^{11}\text{Be} \) populated by the \( \beta \) decay of a laser polarized \( ^{11}\text{Li} \) at TRIUMF [25].

The magnetic moments of \( ^9\text{C} \) and \( ^{13}\text{O} \) were measured to extract the isoscalar magnetic moments for \( A = 9 \) and \( A = 13 \), \( T = 3/2 \) mirror pairs [26], and the spin expectation values \( \langle s \rangle \) deduced from them were used for a stringent test of nuclear structure theories.

**Exploring a Domain of Anomaly**

Neutron-rich isotopes of Ne, Na, and Mg with neutron numbers \( N = 20 \) have been known to show anomalously large binding energies and lowered first \( 2^+ \) excited states [27], and later experimental and theoretical works [28,29] revealed that the ground states in this region of isotopes were dominated by unusual nucleon configurations, with significant shape deformations. This region of neutron-rich nuclei around the magic number \( N = 20 \) is named the island of inversion. The island of inversion may extend beyond the elementary line of Mg, and may show a diffuse or clear-cut border, depending on what mechanism underlies the onset of such an anomaly. Investigations in neutron-rich isotopes of Al are in progress by making use of nuclear moments; the \( \mu \) and \( Q \) moments as probes into nucleon configurations and nuclear shapes, respectively. Results obtained so far [30–33] for \( ^{30}\text{Al}, ^{31}\text{Al}, ^{32}\text{Al}, \) and \( ^{33}\text{Al} \), suggest that the “northern” borderline of the island is likely to run between Mg and Al isotopes for \( N = 19 \) and 20, with a possible diffusion into \( ^{31}\text{Al} \) at \( N = 20 \).

Finally, I remark that currently the nuclear structure studies in the regions far from the stability line through nuclear moments are actively being conducted in several institutes in the world [34–40].

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References
The Nuclear Microprobe

Introduction and New Developments in Beam Optics

Nuclear microprobes are used in many accelerator laboratories for a range of applications in microanalysis and modification of a wide variety of different materials. They are used to focus MeV ion beams to small spot sizes containing currents ranging from femtoamperes to nanoamperes. While microprobes routinely achieve spatial resolutions of a few micrometers, recent breakthroughs in lens design and accelerator technology have achieved resolutions of less than 100 nanometers and a state-of-the-art value of about 35 nm. This article gives a brief overview of the current state-of-the-art of microprobe performance and recent applications in different disciplines in microanalysis, focused irradiation, and micromodification.

Figure 1(a) shows a schematic of the important components of a microprobe. A MeV ion beam from an electrostatic accelerator passes through an object aperture, then through a collimator aperture that limits the beam divergence. The quadrupole lenses form a demagnified image of the object aperture on the sample surface. MeV ions have a high magnetic rigidity so conventional solenoid lenses are not strong enough to focus them (although a superconducting solenoid has been used) so magnetic quadrupole lenses are normally used as the focusing lenses. The main drawback of quadrupole lenses to form a point focus is the greater complexity of the focusing system. A single quadrupole lens only focuses in one plane and defocuses in the orthogonal plane, so more than one lens is needed to form a point focus. Most microprobes therefore use combinations of 2, 3, or 4 quadrupole lenses with alternating polarities and different strengths to focus MeV ions to a small spot. Accounts of quadrupole lens optics specific to microprobe probe-forming systems may be found in Ref. [1].

Demagnification of the microprobe is approximately given by the object distance divided by the image distance, and larger demagnification typically gives smaller beam spot sizes. The focused beam spot is scanned over the sample surface using magnetic coils or electrostatic plates and the beam scanning coordinates are fed to the data acquisition computer along with the energy of the recorded signal for microanalysis, enabling spatially resolved images to be recorded. For materials modification, the focused beam is scanned over the sample surface under computer control with the fluence at each point separately controlled to build up any arbitrary damage pattern.

A typical microprobe has a large image distance of about 20 cm, required for the location of X-ray, backscattering detectors, and optical microscopes, which need a clear path to see the front face of the sample. In conjunction with long quadrupole-lens lengths of about 10 cm a demagnification of about fifty is achieved. For a typical normalized beam brightness of 1 pA/μm² mrad² MeV supplied by megavolt electrostatic accelerators, this enables several hundred picoamperes...
to be focused to a spot size of about 1 \( \mu \text{m} \). Recently it was shown that a new type of shorter, stronger quadrupole lenses and a re-designed target chamber with an image distance of only 7 cm allowed a new generation of high demagnification microprobes to achieve demagnifications of about 150 \cite{2}. This has enabled much smaller beam spot sizes, albeit at low currents of femtoamperes (Figure 1(b)).

An important factor that limits spatial resolution is the energy spread of the beam, due to fluctuations of the accelerator terminal voltage. This increases the size of the focused beam spot as ions of different energies are focused to slightly different positions in the image plane owing to chromatic aberrations of the quadrupole lenses. This is the main reason why cyclotron accelerators with their large beam energy spread are not ideal for microprobe use. Typical fluctuations of hundreds of Volts from single-ended or tandem Van de Graaff accelerators give a MeV ion beam a fractional energy spread of about \( 10^{-4} \), which does not significantly limit beam resolution. However, the energy spread also results in a fluctuating beam current that makes it difficult to uniformly scan the focused beam over an area. A new generation of solid state electrostatic accelerators \cite{3} has achieved very small terminal voltage fluctuations of tens of Volts, giving a fractional energy spread of about \( 10^{-5} \), which make them ideal for use in conjunction with high demagnification microprobes.

**Applications of Nuclear Microprobes**

The most common applications of microprobes are for elemental microanalysis, based on the use of proton induced X-ray emission (PIXE), Rutherford backscattering spectrometry (RBS), and nuclear reaction analysis (NRA) to measure spatially resolved trace element quantities in many types of materials across many disciplines, such as biology, biomedicine, geology, environmental science and archaeology, metallurgy, and materials science. Because elemental microanalysis requires beam currents of a few hundred picoamperes a resolution of about 1 \( \mu \text{m} \) is achieved.

Apart from elemental microanalysis there are also a wide variety of other types of microanalysis available using a microprobe, such as ion beam induced charge (IBIC) microscopy, device upset sensitivity using single event upset (SEU) imaging, defect centers and light emitting properties using ionoluminescence (IL), areal thickness and density variations using scanning transmission ion microscopy (STIM), and surface topography using secondary electron emission. A feature of these techniques is that they typically require low beam currents of 1 fA to 1 pA because each incident ion can produce a measurable event, so spatial resolutions of 100 nm are achieved.

**Trace Element Microanalysis**

PIXE is the most widespread of microprobe techniques, being widely used for microanalysis and imaging of biological and biomedical samples \cite{4}. The relatively large production cross-sections make it easy to generate spatially resolved images of elemental distributions. PIXE is capable of quantitatively imaging elemental distributions to a sensitivity of parts per million, whereas electron probe microanalysis (EPMA) typically detects concentrations of parts per thousand. On the other hand, secondary ion mass spectrometry (SIMS) can achieve a detection sensitivity of parts per billion, but tends to suffer from a lack of quantitivity and matrix-dependent measurements. One important aspect of such biomedical studies using PIXE is that they rely on having some means of recognizing the tissue sample area under analysis. There are various ways of doing this using optical or fluorescence microscopy of stained tissue, or using STIM, which provides an elegant solution for imaging and locating specific cellular features of unstained tissue. Figure 2 shows microprobe images of cells, combining STIM images for location and PIXE images of the potassium and cesium distributions \cite{5}. By further processing of these two PIXE images it was deduced that the potassium and cesium are co-localized, with both elements showing the same intra-cellular distributions.
Solar and cosmic radiation result in the production of electron-hole pairs in the semiconductor and insulating materials in space-based and terrestrial microelectronic devices, which are used in satellites and other high-radiation environments. This excess charge can result in various forms of upsets to device memories and functioning. A related technique to IBIC is SEU imaging [7], which provides a means of producing spatially resolved images of the upset sensitivity of a microelectronic device area by irradiating it with a focused beam of high energy heavy ions in a microprobe that is specially designed to focus such ions. By correlating the spatially resolved upset sensitivity in conjunction with IBIC images and design masks, the components that are most likely to cause upsets can be identified, enabling savings in both cost and time in the design of radiation-hardened devices.

**Single Heavy Ions for Application in Biology**

An increasingly popular use of microprobes is in-vitro cell irradiation, in which a predetermined number of ions are delivered to specific locations. Individual cells or subcellular components such as cell nuclei, cytoplasm, or membrane may be targeted and a specific ion fluence delivered, allowing radiobiological studies of cells that cannot be easily performed by other approaches. Applications include studying the response of cells to internal and external stimuli and radiation, cancer therapy, and occupational risks of exposure to radiation. Because light ions such as protons and helium do not have a large enough linear energy transfer to induce many types of cell damage, heavy ions with much higher rates of linear energy transfer, such as oxygen or iron at energies of 50 to 200 MeV, are typically used. These can induce a wide range of cell damage mechanisms such as DNA double-strand breaks, which can lead to cell death or mutations.

This particular range of ion species and energies are only available at a few microprobe facilities, such as Ref. [8] together with specially designed lenses to focus them owing to their high magnetic rigidity. Great care must also be taken over collimating the beam current to very low levels such that individual ions can be controllably delivered to specific locations, and limiting the beam damage to the sensitive collimating apertures. There are different approaches to constructing the beam delivery system for such irradiation facilities. A microprobe quadrupole focusing system can be used to provide a controllable, scanning beam irradiation facility with the beam brought into air through a thin window. The dish holding

![Figure 3](image)

**Figure 3.** Spatially resolved TRIBIC results showing the measured hole pulse rise time in a single crystal diamond, at different biases. The time-resolved variation of the charge pulses at different applied bias voltages and temperatures indicates a reduced charge carrier velocity caused by a polarization-induced reduced effective field strength. Reprinted from Ref. [6].
the cells is ideally horizontal, requiring a vertically mounting focusing system, although horizontal microprobes have been reliably used.

Figure 4 shows an example of accurate targeting and irradiation achieved within individual cells performed on the Munich microprobe using heavy ions [9]. Fluorescence imaging of tissue that contained DNA specific stains was used to locate and identify features within the microprobe chamber prior to irradiation. A targeting accuracy of about 2 \( \mu \text{m} \) was demonstrated in the form of crosses produced on each irradiated cell, produced by individual ion hits in a pre-determined pattern (Figure 4(b)).

Micro- and Nano-Scale Patterning

Several microprobe groups are now developing the use of proton beam writing, in which a microprobe is used to direct-write a pattern in a polymer, rendering it more or less easily removed by subsequent chemical development. This has proved very effective in fabricating high aspect ratio structures for uses in MEMS technology, microphotonicics, and microfluidic devices. Compared with electron beam lithography for example, high resolution patterning of thick layers is possible because MeV ions are not significantly scattered through the first few micrometers, whereas keV electrons are heavily scattered. Figure 5(a) shows a test structure that was fabricated in the negative resist material SU8, in which an aspect ratio of well over one hundred is achieved [10].

While proton beam writing may be used for high spatial resolution patterning over small areas, a microprobe-based process was recently developed to pattern and fabricate components on a micrometer lateral scale but over wafer areas of several square centimeters [11]. This process is based on a microprobe lens system to project a uniform distribution of MeV ions over a wafer area, which is coated with a patterned resist layer. The microprobe collimator and object apertures are opened wide to give a focused beam current of several hundred nanoamperes for several hundred nanoamperes within the chamber. Fluences of \( \sim 10^{14} \text{ cm}^{-2} \), typical of those required to form silicon-based photonics microcomponents in conjunction with electrochemical anodization, are achieved in minutes. A significant advantage of this approach is...
compared to simply sweeping an unfocused beam over the wafer surface is that any beam current fluctuations are uniformly distributed over the whole irradiated area so very high spatial uniformity of irradiation is achieved. It has been used to fabricate a variety of porous silicon-based photonic components such as Bragg reflectors and waveguides. Figure 5(b) shows a large area of porous silicon that was patterned with different color distributed Bragg reflectors using this approach.

In summary, there are over fifty microprobe groups around the world, involved in a wide range of studies of micro-analytical work in biology, biomedicine, materials analysis, geology and archaeology, and micro-modification using a range of light and heavy ion energies from 1 to several hundred MeV. Some concentrate on more traditional ion beam analysis applications whereas others now commonly use low beam current applications for microanalysis and micro-modification of materials. The best reported resolution to date is about 35 nm, with several new microprobe designs presently under construction that will try to push this toward 10 nm. This will provide even more scope for developing new and existing applications of highly focused MeV ion beams.

References

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The 23rd Particle Accelerator Conference

PAC09, the 23rd Particle Accelerator Conference, organized by the TRIUMF laboratory under the auspices of the APS-DPB and IEEE-NPSS, was held in Vancouver, B.C., Canada, May 4–8, 2009. PAC09 was an outstanding conference by any measure: 1,327 participants from 31 countries, 74 industrial exhibits, 148 students, 197 orals totaling 79 hours, 1,570 posters, and 23 satellite meetings. Making all that run smoothly and confidently is an achievement of which TRIUMF can be proud.

What the statistics cannot capture was the vitality of the meeting: several standing-room-only oral sessions, the throng of the enthusiastic and energetic poster sessions, and the myriad technical conversations—all of these are indicators of the strength and creativity of our field. An important component was the presence of students, “apprentice” accelerator physicists and engineers; many of them attended the student poster session that overlapped the delegates’ reception. PAC09 took seriously its responsibility to engage students: they are the future of our field. Fifty-one students received full travel grants directly from PAC09 and its sponsors.

Particularly memorable were the packed rooms for four talks: R. York’s FRIB: A New Accelerator Facility for the Production of Radioactive Beams; M. Hogan’s Road to a Plasma Wakefield Accelerator based Linear Collider; P. Emma’s Commissioning Status of the LCLS X-Ray FEL; and T. Haberer’s Commissioning of Hadrontherapy Synchrotrons HIT and CNAO. These talks cement the opinion that particle accelerators are key to several frontiers—astrophysics, nuclear/high-energy physics, materials science, and nuclear medicine—and will contribute to profound discoveries in them all. This same thought was echoed at the opening plenary in M. Turner’s 400 Years of Discovery with Telescopes and Microscopes, and N. Walker’s rallying call Progress Toward the International Linear Collider (ILC). For our community, this sense of scope and achievement for our craft more than made up for the disappointment over the too-short-lived Large Hadron Collider (LHC) Commissioning, as reported by J. Weninger. Heartening too was news that ILC R&D efforts in the United States and United Kingdom are starting to rebound after the budget cuts in December 2008, while work in Asia and Europe has continued strong. Evidently, we are resilient.

Picking “highlights” and crystal-ball gazing are precarious activities: the first guaranteed to offend some of the un-chosen majority, the second likely to garner the harsh verdict of retrospection. Nevertheless, I shall indulge myself by doing both; and focus on the talks by Turner, Hogan, and Hajima.

A unifying theme of the opening plenary, the International Year of Astronomy, was alluded to directly by Turner. The invention of microscopes and telescopes 400 years ago marked the birth of modern science. Their separate paths to inner and outer space have converged, merging the frontiers of nuclear- and particle- and astrophysics along with a transformation from observation to explanation. Both instruments (microscope and telescope) have seen a 10^{12} times improvement in performance. Microscopes have metamorphosed into particle accelerators: from electron microscopes to high-energy colliders they have accumulated most of the components of the Standard Model of elementary particles and forces, and their collective manifestations such as the chart of the nuclides and quark-gluon plasmas. Both instruments will shed light on (i) how neutrinos shape the cosmos; (ii) origin of baryons; (iii) identification of Dark Matter; (iv) understanding of Dark Energy; and (v) the origin of the Universe. Accelerators (e.g., LHC, ILC) provide a means for studying the heavenly laboratory under controlled conditions. This same statement was made by Shotter in the context of the stellar paths of element evolution from the primordial H and He. To measure the chemical composition of stars and details of nuclear processes we use sophisticated telescopes and accelerators, respectively. In particular, for “fast processing” measurements are made on unstable nuclides using rare isotope beams (RIB) at ISOL facilities such as CERN-ISOLDE and TRIUMF-ISAC, and fragmentation facilities such as RIKEN, MSU-NSCL and the future Rare Isotope Accelerator at MSU. The use of RIB for astrophysics is a concrete example of the convergence of astronomy and nuclear physics and accelerators.

What will be the successor (or rival) of ILC? Hogan suggested it will...
be a Plasma Wakefield Acceleration (PWFA) based linear collider. Talked of since the late 1970s, PWFA has made tremendous progress in the last two decades: the energy scale of laser-driven has grown from 10 MeV to 1 GeV, and that of beam-driven up to 40 GeV/electron. Hogan focused on the latter. In a two-beam accelerator, the witness bunch encounters a gradient of \( E > 10 \, \text{GV/m} \)—in the early days sustained only over 0.1 mm. The understanding grew and has culminated in 50 GeV gain in 1 meter. The present concept for a PWFA e+e- collider captures three decades of RF linac R&D into the drive accelerator, whose time-sliced beam feeds two opposing cascades of PWFA cells. The concept assumes a 25 GeV CLIC Test Facility type drive beam and 20 cells per witness beam to reach 1 TeV center of mass. The proposed FACET facility, harnessing the SLAC linac, is intended to investigate impediments and iterate the concept through experiments. The PWFA cell relies on the fact that 100 fs bunches bring large gradients and long (1 m), uniform, high-density plasma. Space-charge fields of the drive beam tunnel-ionize the Li gas, so there are no timing or alignment issues. Goals of the FACET proposal, which envisages a 5 year program starting in 2010, are to energy double a 25GeV beam in 1 m, and demonstrate much-reduced energy spread and 30% efficiency between drive and witness beam. Stay tuned . . .

Accelerators have also independent lives in materials- and life- and medical-sciences: neutron and X-ray microscopes such as SNS at Oak Ridge and the Linear Coherent Light Source (LCLS), respectively; and isotope production for therapeutics at TRIUMF, and hadron oncology at Heidelberg Ion-beam Therapy (HIT), for example. Of these applications, it is only the light sources that are poised for orders of magnitude performance improvement. R. Hajima’s talk Status and Future Perspectives of ERLs expanded on the source of that improvement.

Energy Recovery Linacs, first proposed by Tigner in 1965, have taken 40 years of technological improvement to become practicable. In an ERL, energy is first extracted from the cavity EM field through acceleration and then, later, returned via deceleration. Between these moments, the higher energy electron beam may be used to amplify or otherwise manipulate imposed modulations (e.g., to generate EM radiation). Although the first (JLab IR-Demo) and most recent (Daresbury ALICE) ERL facilities are light sources, planned applications extend also to coherent electron cooling of relativistic ion beams (and electron collisions with them) at the Relativistic Heavy Ion Collider and polarized positron generation for e+e- colliders. There are also proposals for X-ray sources based on laser Compton scattering. The fundamental unity of these applications lies in the use of a high current and energy electron beam as means of manipulating/amplifying EM energy/photons—a unity that harks back to the first electron tubes and klystrons. The use of a one- or few-pass linac facilitates high beam quality and the preservation of exquisitely small beam emittances. The energy recovery enables high beam current/power at low cost (electrical power bill), and SCRF enables continuous-wave operation and high bunch repetition rate. Non-energy-recovered machines are pulsed with low repetition. The ERL/SCRF combination makes feasible extreme peak and average brilliance and near 100% coherence of the emitted photon beams, even for hard X-rays, allowing them to out-shine existing FELs and contemplate single atom experiments. With such strong credentials, it is no surprise that there are several proposals for multi-GeV ERL driven sources of X-rays (e.g., Cornell, Argonne APS, KEK). Crucial to all ERL applications are advances in high-brilliance electron guns and high beam current operation of SCRF. The former is addressed by photo-cathode and SRF gun development; and the latter by input coupler, HOM load, and piezo-tuner improvement. Both are also of great importance to ILC. Given the ubiquity of applications and multiplicity of proposals, ERLs are destined to have a bright future.

Finally, PAC09 wishes a similar good fortune to the three following conferences: PAC’11, the next in the continuing North American series, to be hosted by Brookhaven National Laboratory in New York City; the IPAC’10 in Kyoto Japan, the first of the 3 year international cycle; and the IPAC’11 in San Sebastian, Spain.

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24O: A Doubly Magic Nucleus at the Neutron-Drip Line

Nucleon magic numbers have formed a fundamental basis of the nuclear shell structure for the last fifty years. The magic numbers (N, Z = 2, 8, 20, 28, 50, 82, 126) were thought to be invariant over the entire nuclear chart. Recent investigations with nuclei far from β-stability have, however, sprung a new world of surprise. The first empirical signatures from systematics related to nuclear binding showed that the conventional magic numbers disappear in very neutron- or proton-rich regions. This does not mean that shell structure is dissolved. On the contrary, new nucleon numbers seem to show magic (or shell closure) characteristics. The first such new shell closure was suggested at N = 16 for neutron-rich nuclei. Systematic trends of proton separation energies showed that the conventional Z = 8 shell closure persists in these neutron-rich regions. These features suggest that 24O, which is the last bound oxygen isotope, is potentially a candidate for being a new doubly magic nucleus.

To establish 24O as doubly magic, an international team of scientists investigated how the neutrons in this nucleus are arranged. The experiment was performed at the fragment separator FRS at GSI, Darmstadt Germany (Figure 1). The synchrotron at GSI was used to produce 24O at a rate of only 3 particles per second, accelerated to relativistic energy of 920A MeV. This highly energetic beam hit a thick block of carbon. The interaction process removed a neutron from 24O. The detectors placed at the final focal plane of the fragment separator FRS at GSI recorded the momentum distribution of this process. The interaction process removed a neutron from 24O. The detectors placed at the final focal plane of the fragment separator FRS at GSI recorded the momentum distribution of this process. The momentum distribution is directly linked to the wavefunction of the neutron being removed. In this way, it was confirmed that the outermost neutrons in 24O almost solely reside in the s-orbital (l = 0) with no observable occupancy in the neighboring d-orbital (l = 2) (Figure 2). This observation therefore establishes a spherical magic number at N = 16 in 24O, confirming suggestions for it to be a new doubly magic nucleus at the neutron drip-line. The article is published in Phys. Rev. Lett. 102 (2009), 152501.

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Figure 1. View of the experimental set-up at the FRS, GSI.

Figure 2. The longitudinal momentum distribution data (circles) for one-neutron removal from 24O. The red (blue) curves show theoretical predictions for the neutron being removed from the s-(d-) orbital.
2009

**September 14–18**
Tokai, Ibaraki, Japan. 10th International Conference on Hypernuclear and Strange Particle Physics (Hyp-X)

**September 16–18**
Istanbul, Turkey. 5th Workshop on Shape-Phase Transitions and Critical Point Phenomena in Nuclei
http://workshop.turkfiizikdernegi.org/

**September 27–October 3**
Milos, Greece. Electromagnetic Interactions with Nucleons and Nuclei (EINN 2009)
http://www.iasa.gtr/EINN_2009/

**September 27–October 3**
Lacanau, France. Joliot-Curie Nuclear Physics School
http://www.cenbg.in2p3.fr/joliot-curie

**September 28–October 2**
Sochi, Russia. International Symposium on Exotic Nuclei EXON 2009
http://exon2009.jinr.ru

**October 5–8**
Bordeaux, France. Compound Nuclear Reactions and Related Topics
http://www.cnr09.com/

**October 5–9**
Messina, Italy. International Conference on Nuclear Reactions on Nucleons and Nuclei
http://uncleo.unime.it/conf2009/

**October 5–10**
Dubna, Russia. NuSTAR Meeting

**November 4–7**
Catania, Italy. International Workshop on Multifragmentation and Related Topics (IWM2009)
http://agenda.ct.infn.it/
conferenceDisplay.py?confld=128

**November 29–December 4**
Napa, California, USA. 4th Asia-Pacific Symposium on Radiochemistry (APSORC’09)

**December 16–19**
Tallahassee, Florida, USA. Direct Reactions with Exotic Beams (DREB2009)
http://dreb2009.physics.fsu.edu/

**2010**

**May 31–June 3**
Madrid, Spain. NuPECC LRP Town Meeting
http://www.nupecc.org/index.php?
display=misc/meetings

**June 6–11**
Lamoura, France. EURORIB 2010
http://indico.cern.ch/conferenceDisplay.py?confld=61310

**June 7–12**
Kyiv, Ukraine. Current Problems in Nuclear Physics and Atomic Energy
http://www.kinr.kiev.ua/NPAE-Kyiv2010/

**July 2–7**
Torino, Italy. Euroscience Open Forum ESOF2010
http://www.esof2010.org/

**July 4–9**
Vancouver, Canada. INPC 2010
http://inpc2010.triumf.ca/

**July 19–23**
Heidelberg, Germany. Nuclei in the Cosmos NIC XI
http://www.sw.uni-heidelberg.de/nic201

**August 9–13**
Fort Worth, Texas, USA. International Conference on the Application of Accelerators in Research and Industry CAARI 2010
http://caari.com/

**September 13–17**
Athens, Greece. 10th European Conference on Accelerators in Applied Research and Technology (ECAART10)
http://www.ecaart10.gr

**September 27–October 2**
Juelich, Germany. The 19th International Spin Physics Symposium (SPIN2010)
http://www.fz-juelich.de/ikp/spin2010

**September 27–October 2**
Juelich, Germany. SPIN2010 - The 19th International Spin Physics Symposium
http://www.fz-juelich.de/ikp/spin2010

More information available in the Calendar of Events on the NuPECC website: http://www.nupecc.org/