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FEATURING:
ALTO • Spin Program at COSY-ANKE
Precision Mass Measurements • CRIS
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Cover Illustration: ALTO: The first ISOL facility based on photo-fission (see article on page 5).
News from NuPECC

The last editorial from the chair of NuPECC (Nuclear Physics News, Vol. 21, No. 1) concerned the presentation of the Long Range Plan, which took place in December 2010 (see http://www.nupecc.org/index.php?display=pub/publications). I think it is time to inform about what NuPECC is doing after such an important effort.

Due to the typical time span of the Nuclear Physics projects it is expected that the activity for the next Long Range Plan might start approximately in a couple of years. Therefore the natural question is: What is NuPECC doing these days? The aim of this editorial is to briefly answer this question and to stress the contribution that this committee is continuously giving to promote nuclear science and to keep strong ties with the appropriate committees giving directions in Nuclear Physics also outside Europe.

I will focus mainly on the following three points: (1) the follow-up of the Long Range Plan and its role in the preparation of proposals for requesting EU funding; (2) NuPECC and the European Science Foundation; and (3) a new initiative related to preparation of a volume on “Nuclear Physics for Medicine,” in the context of our activities for spinoff.

Follow-Up of the Long Range Plan

The follow-up of the Long Range Plan is a continuous activity and certainly a duty of NuPECC. Presentations and discussions regularly take place at our NuPECC meetings focusing on the facilities presently under construction, in particular the ESFRI facilities FAIR and SPIRAL2. These reports are also very useful in preparation of the NuPECC reports at the meetings of the WG.9 committee of IUPAP that are taking place every year. The WG.9 committee was established by C12 (the IUPAP Commission on Nuclear Physics) to stimulate and foster international cooperation in our field. Among the IUPAP committees WG.1 is ICFA, the International Committee on Future Accelerators, which plays such an important role in particle physics. The members of WG.9 include representatives of most of the major nuclear physics laboratories, as well as the Chairs and past-Chairs of C12, NuPECC, and NSAC. In 2012 I participated in the WG.9 meeting that was organized at RIKEN (in 2013 the WG.9 meeting will be in LNF–Frascati [Rome]). On that occasion I presented an overview of the nuclear physics facilities and related activity with emphasis on the progress made since our last Long Range Plan of 2010. The advances in the construction of the facilities in the NuPECC road map were presented at the 2012 meeting and discussed together with the major planning in Europe and worldwide for the next years. In addition it was stressed that the ELI_NP facility (for high resolution gamma beams; http://www.eli-np.ro), that was just proposed at the time of the Long Range Plan, has been approved by the Rumanian government.

In the context of the follow-up of the Long Range Plan it is important to say that NuPECC has participated as observer in the preparation of Particle Physics Strategic Planning. For the ALICE experiment at LHC the NuPECC recommendations were further endorsed.

Presently the time lines for the construction of the new facilities are, for several and different reasons, moving forward as compared with the past plans. This is a general problem worldwide and therefore it is important to keep the community strongly involved both in the preparation of the new facilities but also in physics programs that could fill well the gap between the present knowledge and the ambitious future aims using the existing facilities in the best possible way. To keep updated on these issues and decide upon a common strategy are key actions particularly in view of the preparation of proposals for EU funding. At NuPECC meetings there are always reports about the EU Integrated Activities (ENSAR and HADRON PHYSICS), which contribute to access to the large-scale facilities and partly support the new developments and the networking. The recent and near future discussions are going on about how to efficiently prepare the proposals within HORIZON20 and to find opportunities to enhance the EU contributions to large- and small-scale facilities. The cooperation with laboratories and funding agencies and the collaborations among scientists are essential to carry out the long-term ambitious programs, the ones set up within ESFRI (FAIR and SPIRAL2) but also those of smaller size such as HIE-ISOLDE (CERN) and SPES (LNL). It is important to note that a good step forward was made with the ERA-NET NuPNET (ended in 2011).
in the direction of setting up more commonly funded projects involving several European agencies and-based to major research European infrastructures.

**NuPECC and the European Science Foundation**

NuPECC in 1991 became an expert board on the European Science Foundation. Because of this the NuPECC chair attends the general meeting of ESF and thus gets some grasp on the European Science Policy and responds to the specific questions addressed to expert boards.

In the last two years a reorganization process with ESF has started in order to fit with the presence of the very new organization Science Europe (launched one year ago). Indeed after discussions about how research funders can have the most influence in the European Research Area (ERA), the situation has been clarified. Science Europe—a Brussels-based organization is now well-placed to contribute a strong policy role to the ERA. In parallel with the ramping up of Science Europe, the ESF commenced the responsible winding down of some of its traditional activities. For Expert Boards and Committees (EBCs) Science Europe and ESF maintain their opinion that they are a very important contribution to the successful development of the ERA. The ESF Governing Council took careful note of the results of the independent—and very positive—evaluation of the EBCs carried out in 2011. Alternative hosting models after 2015 are being prepared with the help of ESF. The objective is to keep all the expert boards under the same umbrella.

It is clear that the birth of a new organization and the process of the possible ending of ESF have an impact on NuPECC that is presently moving in the direction of making an alliance with the other expert boards to be in a common framework.

**Nuclear Physics in Medicine**

NuPECC is planning to produce a booklet on “Nuclear Physics in Medicine” in the context of the outreach activity. In contrast to the “Long Range Plan” this booklet is not aimed to be a position paper but will serve to give a comprehensive overview of how fundamental nuclear-physics research (in its broadest sense) had and will continue to have an impact on developments in medicine. It is expected to reflect the state-of-the-art as well as future prospects. The document will serve to inform the scientific community (beyond the nuclear-physics community), the funding agencies and policymakers, as well as the politicians. Three different chapters have been identified for the paper, namely hadron therapy, imaging, and medical radioisotopes. A good balance will be found between reporting about the past achievements on impact of nuclear physics in medicine and the new developments in the pipeline of being implemented.

For the preparation we are involving several experts in the field (http://www.nupecc.org/index.php?display=wpmed/working-groups) and discussions at all levels, including a town meeting, are planned to take place.

To conclude I like to say that this short editorial does not cover all the items that are on the agenda of our meetings. I thank all NuPECC members for their very important work and for being very involved in all the activities, ideas, and initiatives carried out by the committee.

Special thanks to Sissy Körner who is working with continuous dedication not only for NuPECC but also for Nuclear Physics News. I would like to point out that Sissy has also recently organized the compilation of the very useful booklet of facilities (http://www.nupecc.org/pub/hb12/hb2012.pdf).

Angela Bracco
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NuPECC Chair
The ALTO Facility in Orsay

Introduction

The Institute of Nuclear Physics at Orsay (IPN-Orsay) has always been a major player in building accelerators for nuclear physics. Already at the time when the first synchrocyclotron had been built at CERN, IPN-Orsay had been operating and exploiting its first accelerator (a synchrotron that had been built by Frederic Joliot and around which the institute was founded). During the 1990s the phasing out of two of the IPN accelerators, the heavy-ion Linac + cyclotron system ALICE and the proton synchrocyclotron, was done timely with GANIL reaching its full performances. IPN Orsay was and still is a key player both during the construction and the exploitation of GANIL facilities. Later on and after building and delivering the superconducting cyclotron AGOR to KVI, the institute started a steady R&D program on ISOL production techniques, which is a long-standing tradition of the institute. It is for instance worth reminding that ISOL techniques were extensively developed at the synchrocyclotron of Orsay during the early 1960s into the end of the 1990s with an important impact on what has been achieved during decades at ISOLDE-CERN.

This recent rebirth of the ISOL R&D activity at IPN has inspired the ALTO project.

For a long time the ALTO acronym stood for “Linear Accelerator next to the Orsay Tandem” and refers to the newly built ISOL facility within the same building as the Orsay Tandem. Since the beginning of ENVAR, ALTO refers more to the whole TNA (Trans National Access) facility and the acronym stands since then for “Linear Accelerator and Tandem at Orsay.” This article will be mainly focusing on the ISOL part of the ALTO facility.

Description of the facility

The ALTO facility is powered by two major accelerators: a 15 MV MP-Tandem to provide stable beams and a 50 MeV linear electron accelerator dedicated to the production of radioactive beams induced by photo-fission process [1]. The facility offers the opportunity to produce, within the same place, cluster beams for interdiscipli-nary physics and stable and radioactive beams for astrophysics and nuclear physics. The delivered beams are dedicated to a large range of physics programs from nuclear structure to atomic physics, cluster physics, biology, and nanotechnology. For the production and delivery of stable ion beams, the Tandem runs on average 4,000 h/year, which allows to schedule roughly 30 weeks for experiments. The Tandem can provide beams of about 75 species ranged from proton to Au and cluster beams. The delivered stable beams represent typically 20% of light ions (proton to $^4$He), 60% of heavy ions ($^7$Li to $^{127}$I), and 20% of cluster ions Cn, CnHm.

Regarding the RNB, the production mode is based on the photo-fission process of a thick UCx target heated up to 2,000°C and using the ISOL technique (Figure 1). The driver is an electron linac of 50 MeV/10 µA. It is composed with a 3 MeV injector (90 kV thermionic gun and a bunching system working at 3 GHz) and an accelerating section that provides an...
energy gain of 47 MeV. The beamline consists of two dipole magnets and six magnetic quadrupoles. It is equipped with beam diagnostics for the measurement of current, beam position, energy, and energy spread. The Security and Control system uses an industrial device for the supervision. The RF power, for the electron linac, is delivered by one 3 GHz klystron and a modulator.

The electron beam is directed toward the production unit, which is located inside a bunker, and the released fission fragments from the target are ionized with $1^+$ charge state and transported on a 30 kV platform to the mass separator (with a mass resolution of $\Delta A/\Delta A = 1,500$). The production target is composed of 150 disks of $^{238}$UCx of 14 mm diameter and 1 mm thickness. The target is heated up to 2,200°C (3 kW electric power) using a Tantalum oven. The expected in-target productions at ALTO using 50 MeV incident electron beam with 10 $\mu$A averaged current correspond to $10^{11}$–4 $10^{11}$ fissions/s.

For the ionization of the released fragment of fission, three ion source types can be coupled to the target: Febiad ion source, surface ion source, and laser ion source. The resonant ionization laser ion source, RIALTO (Resonant Ionization at ALTO) has been installed recently at the facility. After having performed off-line tests for the production of Sn, Cu and Ga, on-line beams of Ga have been selectively and efficiently produced and delivered to experiments. RIALTO is based on the dye laser technology. It is equipped with a Nd:YAG (100 W, 532 nm) pump laser from Edge wave operating at 10 GHz, two (540–850 nm) dye lasers from Radiant Dyes, and BBO doubling units (270–425 nm). In the on-line test on the Ga production, an ionization efficiency of more than 10% at full electron beam intensity has been measured. We have planned to upgrade the laser system by adding a third dye laser to achieve the possible three-step ionization schemes for the production Ni, Ge, Sn, Sb, and Te. In addition, we have designed a reference cell equipped with an oven and a detection system based on $\mu$channel plate. This cell will be used before on-line runs to tune the different laser wavelengths by measuring the current of the ions of interest obtained by the interaction of lasers and the evaporated atomic flow. This setup will be also used for the development of unknown laser ionization schemes and also for the laser ionization tests.

In June 2006, the first tests of production of neutron rich fission fragments have been allowed by the safety authorities. The electron beam limited to an intensity of 100 nA and an energy of 50 MeV hits the target containing 60 g of $^{238}$U. We first have confirmed that the radioprotection measurements fits with our calculation performed. The calculated predictions were done taking into account the release time of the different elements and the half life of the different isotopes. Measurements of fission fragments production have then been performed during the first ALTO experiment after separation from the mass 78 to the mass 145. Figure 2 represents the production measured during this experiment and extrapolated to 10 $\mu$A beam current. The productions of the refractory elements could not be measured. These measurements are in total agreement.
with the calculated prediction, and $2 \times 10^5 \, ^{132}\text{Sn}$ and $1.4 \times 10^3 \, ^{78}\text{Zn}$ per second have been obtained with a 100 nA electron beam current [2]. Additional data have been obtained at nominal intensity using surface and plasma ion sources. The extrapolation of the whole measured yields at low intensity is in agreement with the expected yields [3].

Presently, the facility can deliver the radioactive nuclear beams to five different experimental set-ups. One of them is equipped with a new beta-decay spectroscopy set up called BEDO (Beta Decay at Orsay). The principle of this setup is to collect the produced exotic neutron rich nuclei on a tape surrounded by a plastic for beta measurement and 5 Ge detectors placed in very close geometry. BGO shielding and plastic veto for Bremstrahlung allow reduction of the gamma background (Figure 3). A second one, under construction, is dedicated to the nuclear orientation measurements on-line [4].

**R&D at the ALTO Facility**

IPN-Orsay has a long experience in the production of radioactive nuclear beam by ISOL technique [5]. In recent years, developments on targets and ion sources have been achieved mainly for the future SPIRAL2 facility and the European projects EURISOL and ActILab [6]. An active R&D program is underway on both the target and ion source systems at the ALTO facility. The objective is to build up an efficient and reliable system operating in a strong ionizing environment. These systems aimed at producing intense radioactive beams for the next generation of ISOL facilities.

**IRENA Ion Source**

A new plasma ion source of Fe-biada type, named IRENA, has been developed to operate efficiently and steadily under strong radiation conditions [7]. In the conceptual design of the ion source, the radial configuration of the anode–cathode set allows both efficient ionization and the confinement of the positive ions for efficient extraction. In such a configuration no magnetic field is required; this design involves few components for a reliable long-term operation under hard radiation and a reduction of the amount of radioactive waste. The feasibility prototype was designed as close as possible to the EBGP [8] ion source configuration to compare their performances.

To optimize the anode–cathode set and to improve the mechanical and electrical reliability, the second prototype was completely modeled with 3D-Lorentz simulation code (Figure 4) [9]. Due to the difficulty in the manufacturing process, the strip structure of the anode used in the first prototype was modified into a grid one. In addition, 3D Thermal simulations were carried out using the NX-IDEAS simulation code to improve the temperature homogeneity all along the cathode at high temperature (Figure 4).

![Figure 3. BEDO: a versatile and efficient detection system for beta decay studies at ALTO.](image)

![Figure 4. (a) Design of the IRENA ion source obtained by using 3D-Lorentz code; (b) and (c) thermal simulation of the cathode heating: reduction of thermal gradient after a mechanical adjustment.](image)
First off-line tests of the second prototype have shown very competitive performances in comparison to the classical plasma ion source Fe-biad-MK5 commonly used nowadays at ALTO. These tests are still in progress to get the best configuration for the production of radioactive nuclear beams on-line.

Off-Line Tests of Lanthanide Fluorination

For the study of the low-spin states of the neutron-rich lanthanide nuclei located near the mass 160, another R&D work is underway to improve efficiently the production of lanthanide beams by using the fluorination process. Due to their high melting point and chemical reactivity, the lanthanides are known to release slowly from UC₅ targets. Some isotopes such as $^{156}$Pm, $^{159,160}$Sm, and $^{161}$Eu could be released at very high temperature (2,500°C) and ionized as Ln⁺ [10]. Such a target temperature is not yet reachable at ALTO since the running temperature for standard target cannot exceed 2,200°C. The release of lanthanide can be favored by injecting CF₄ in the integrated target/ion-source [11]. Off-line tests have been carried out with stable lanthanide isotopes in order to determine the best running conditions for the production of lanthanide beams. A target obtained from a mixture of lanthanide oxides and graphite has been developed in order to simulate the release properties of the target material using gamma spectroscopy. The obtained results are very encouraging and confirm the possibility to run under safe and attractive conditions, on-line experiments with lanthanide beams at ALTO.

Uranium Carbide Target Development

An R&D program on UCₓ targets has been undertaken at the ALTO facility with the support of Spiral2, Actilab, and EURISOL projects. It has two major objectives: studying the influence of the synthesis parameters on the microstructure, phase coexistence and porosity of the target material, and understanding the influence of those material properties on the release kinetics of the choice nuclei. Different routes of synthesis are under investigation. They can be divided into four categories: the carbo-reduction of uranium oxides and uranium oxalates, nano-structured UCₓ, and the composites by adding sub-microfibers of graphite. Various promising prototypes have been synthesised, they have been systematically analyzed using different techniques to determine the purity, density, porosity, and morphology of the grains and pores. Taking into account recent experimental measurements achieved in collaboration at ISOLDE [12], the Actilab project focuses on highest porosity at the expense of a lower uranium amount.

Five kinds of sample have already been synthesized and characterized [13]. The release efficiency of best samples among the synthesized materials has been determined by measuring the radioisotopes from the target material using gamma spectroscopy. The method is based on the irradiation of UCₓ pellets with deuterons beam of 26 MeV and the measurement of the activity before and after a heating process.

The first results have shown that COMP30 and PARRNe samples have interesting releases at 1,200°C, while OXA sample provides the highest released fraction at 1,550°C. These observed releases could be explained by a high open porosity based on small pores well dispersed within the material.

The program will focus in the future on the reproducibility of the measurements to improve the correlation between the release properties and the characteristics of the samples, in particular at high heating temperature. The best samples will be then selected to be used as a complete target for tests on-line especially for isotopes with very short half lives at ALTO.

First Experiments with ISOL Beams from ALTO

An experimental campaign aiming at studying the stiffness of the N = 50 major shell gap toward $^{78}$Ni via γ-spectroscopy following β-decay has been undertaken for a few years at ALTO. During the first experiments, the radioactive species were created by irradiating the UCₓ target/ion source ensemble with the 26-MeV deuterons beam delivered by the ALTO electron LINAC. Most of the data obtained were largely delivered by the ALTO electron LINAC. The program will focus in the future on the reproducibility of the measurements achieved in collaboration at ISOLDE [12], the Actilab project focuses on highest porosity at the expense of a lower uranium amount.

The two major achievements of the deuteron campaign were γ-spectroscopy study of the neutron-rich nuclei $^{83}$Ge$_{51}$ and $^{81}$Ga$_{50}$ situated in the...
vicinity of $^{78}\text{Ni}$. Excited states of these nuclei could be proposed for the first time and very partial level schemes were proposed. The level pattern that was found in $^{83}\text{Ge}_{51}$ was compared with the one existing in the less exotic $N = 51$ odd-isotones: it was soon understood that we had discovered members of the state multiplet arising from the coupling of the 51st neutron $\nu_{2d_{5/2}}$ to the $2^+_{1}$ state of the underlying $^{82}\text{Ge}_{50}$ core. The first discovery of the low-lying structure of $^{81}\text{Ga}$, which, with $Z = 31$ and $N = 50$, has only three protons more than $^{78}\text{Ni}$, was achieved by the study of $^{81}\text{Zn}$ $\beta$-decay at the PARRNe mass separator [14–15]. Two $\gamma$-rays were clearly observed in coincidence in the decay of $^{81}\text{Zn}$, it was shown that the ground state as well as these two excited states could indeed belong to $^{78}\text{Ni} + 3$ proton configurations involving mainly the $\pi f_{5/2}$ and $\pi 2p_{3/2}$ orbitals. This was a definitive progress towards the understanding of the proton structure in the immediate vicinity of $^{78}\text{Ni}$.

The region was then further investigated, taking advantage of the increased production yields offered by the use of the electron primary beam [16] and radioactive beam purification offered by resonant laser ionization by means of RIALTO [17]. The first laser ionized beam at ALTO was Ga ($Z = 31$). A systematic study of the decays of surface and laser ionized neutron-rich Ga isotopes in the vicinity of the $N = 50$ shell closure was then undertaken. During this campaign, improved level schemes for $^{83,84}\text{Ge}$ (Figure 5) and $^{85}\text{As}$ were obtained [17] and two separate $\beta$-decay schemes of two $^{80}\text{Ga}$ isomers were proposed for the first time [18].

At last, the detection setup at the tape station, used for all these experiments, has been considerably improved over time. For instance, it now hosts a $^3\text{He}$ long-counter, TETRA, built in Dubna, Russia. Associated with a 4 $\pi$–$\beta$ and HPGe detectors it allows $\beta$-n, n-$\gamma$ and $\beta$-n-$\gamma$ coincidence measurements.

The commissioning of this system was done with a $^{123}\text{Ag}$ beam ionized with a hot plasma ion-source, this silver isotope having a well determined $P_n$ value. The efficiency of TETRA was precisely measured via the detection of delayed neutron emission from $^{123}\text{Ag}$ and coincides with that measured with $^{252}\text{Cf}$ source. Then the data on beta decays of $^{124,125,126,127,128}\text{Ag}$ were taken and now is under analysis. A clean and precise measurement of the half-life values of these neutron delayed emitters is possible from the observation of the grow in and decay of the neutron activities. Some periods were discovered with values quite at variance from previously reported ones and the presence of new isomers in odd-odd Ag nuclei close to $N = 82$ is suspected. This could have an impact on calculations of the $r$-process path in this region [19].

Conclusion

The ISOL facility has obtained full authorization to run at nominal pri-
mary electron beam intensity. Since 2012, it is fully open access to outside users via the submission of experiment proposals to the Program Advisory Committee of Tandem-ALTO. The laser ion source of the facility has been successfully tested and has delivered first beams of Gallium. Moreover, set-up equipping a permanent experimental beam-line dedicated to Beta decay studies has been commissioned and is now available. In addition, the construction of the other permanent experimental beam-line for the nuclear spectroscopy is in progress. The R&D program currently in progress at ALTO is determinant for both future and existing ISOL facilities insofar as the target-ion source is the heart system of RNB production. The official inauguration of ALTO that took place in May 2013 will be with no doubt the starting of a long period of exploitation of the facility for the study of neutron rich nuclei with long and dedicated experiments.

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Faiçal Azaiez, Said Essabaa, Fadi Ibrahim, and David Verney

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Results from the Spin Program at COSY-ANKE

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Introduction
It was once claimed that in strong interaction physics “Spin is an inessential complication” [1]. This rather negative attitude ignores certain practical applications and surely dismisses the beauty inherent in many phenomena involving particle polarization. Recognizing this, a program was outlined several years ago to exploit the possibilities of carrying out experiments with polarized beams and targets at ANKE [2]. This facility is based around a magnetic spectrometer sited at an internal target station of the COoler SYnchrotron and storage ring COSY of the Forschungszentrum Jülich. The basic features of the complex were described in a previous issue [3] and we shall here concentrate on a few of the fruits of the spin program.

COSY can accelerate and store polarized protons and vector and tensor polarized deuterons up to momenta of 3.7 GeV/c. In addition to unpolarized hydrogen and deuteron cluster-jet targets, ANKE is also equipped with polarized H → and D → gas target cells so that spin correlations can be studied as well as beam and target analyzing powers.

In the following three sections we first show how, in experiments with polarized deuteron beams at a storage ring, the beam momentum can be determined very precisely through the study of artificially induced depolarizing resonances. This led to a determination of the mass of the h meson that is as precise as any other in the literature.

Beam Momentum Determination and the Mass of the h Meson
A big challenge that one often faces in a precision experiment at a storage ring is the determination of the beam momentum with sufficient accuracy. Although the revolution frequency f₀ can be measured with a relative precision of around 10⁻⁵, there are much greater uncertainties in the exact orbit of the particles in the ring. A way of overcoming this problem was proposed many years ago [4] and has since been implemented at several electron colliders. Spin is here very much the essential element.

The spin of a polarized beam particle in a storage ring precesses around the normal to the plane of the machine. A horizontal rf field from a solenoid can induce depolarizing resonances such that the beam depolarizes when the frequency of the externally applied field coincides with that of the spin precession in the ring. The depolarizing resonance frequency fᵣ depends on the revolution frequency of the machine and the kinematical factor γ = E/me², where E and m are, respectively, the total energy and mass of the particle. For a planar accelerator where there are no horizontal fields, fᵣ/f₀ = k + γG, (1)

where G is the particle’s gyromagnetic anomaly and k is an integer. The combination of the measurements of the revolution and depolarizing frequencies allows the evaluation of γ and hence the beam momentum p.

The depolarizing resonance technique was applied for the first time at COSY with a vector polarized deuteron beam of momenta around 3.1 GeV/c [5]. The deuterons were accelerated with an rf cavity and, once the required momentum was reached, a barrier bucket cavity was used to compensate for the energy losses incurred through the beam-target interactions. The depolarizing solenoid had an integrated maximum longitudinal rf magnetic field of \( \int B_{\text{rms}} d\ell = 0.67 \) Tmm at an rf voltage of 5.7 kV rms. The value of k = 1 in Eq. (1) corresponds to frequencies that were in the middle of the solenoid range of 0.5–1.5 MHz.
A vector polarized deuteron beam leads to an asymmetry in the scattering from a carbon target, which could be measured with the EDDA detector [6]. Since only the frequency of the depolarizing resonance needed to be determined, an absolute calibration of this device at different deuteron momenta was not required. Figure 1 displays an example of this relative polarization as a function of the solenoid frequency for a fixed beam momentum. When the frequency of the solenoid coincides with the spin-precession frequency, the beam is maximally depolarized. The structures, especially the double peak in the center, are caused by the interaction of the deuteron beam with the barrier bucket cavity. However, these did not affect the mean position, which could be fixed with a precision of $10^{-5}$. The full width at half maximum, which was typically in the region of 80–100 Hz, is mainly a reflection of the momentum spread within the beam. If this were the only significant effect, it would correspond to $\delta p/p_{\text{rms}} \approx 2 \times 10^{-4}$.

The other frequency required in the evaluation of Eq. (1) (i.e., that of the circulation in COSY), was measured by using the Schottky noise of the deuteron beam. The statistical distribution of the charged particles in the beam leads to random current fluctuations that induce a voltage signal at a beam pick-up in the ring. The Fourier transform of this voltage-to-time signal by a spectrum analyzer delivers the frequency distribution around the harmonics of the revolution frequency of the beam. As mentioned later, this phenomenon is also used at COSY to measure the luminosity in an experiment [7]. All the data acquired at a particular beam momentum are presented in Figure 2. The small tail seen at low frequencies corresponds to beam particles that escaped the influence of the barrier bucket cavity but still circulated in COSY. The statistical uncertainty in the weighted arithmetic mean was in all cases below 0.2 Hz compared to the typical 1.4 MHz shown in the figure. This means that, under ideal conditions, the left hand side of Eq. (1) could be measured with a precision of better than $10^{-5}$.

The great efforts expended in determining precisely the deuteron beam momentum were justified in order to measure the mass of the $\eta$ meson from the missing-mass peak in the $dp \to ^3\text{He}X$ reaction [8]. For this purpose the experiment was carried out at twelve closely spaced deuteron momenta a little above the $\eta$ threshold and two just below to provide the information required to subtract the multipion background. By exploiting its full geometric acceptance near threshold, it was possible to calibrate the ANKE spectrometer very precisely and thus determine the final $^3\text{He}$ CM momentum $p_f$ for each of the twelve deuteron beam momenta and the results are shown in Figure 3. Although the method depends primarily upon the determination of the kinematics rather than counting rates, its implementation is helped enormously by the fact that the cross-section jumps to its plateau value already by the first point in Figure 3 [9].

The long lever arm facilitates a robust extrapolation to the $\eta$ threshold, where the deuteron momentum was found to be $p_d = 3141.686 \pm 0.021$ MeV/c. There is a one-to-one relation between this and the mass of the meson, which is found to be

$$m_\eta = (547.873 \pm 0.005_{\text{stat}} \pm 0.026_{\text{syst}}) \text{ MeV}/c^2.$$ 

It is in fact the determination of the threshold beam momentum that provides the largest contribution to the $26 \text{ keV}/c^2$ systematic uncertainty. The result is compatible with all
the modern measurements reported by the Particle Data Group [10] that studied the $\eta$ decay and the error bars are as small as any of these. The result suggests that earlier missing-mass determinations, which differed by ~0.5 MeV/c$^2$, lacked the necessary precision.

The Nucleon–Nucleon Program

A good understanding of the nucleon–nucleon (NN) interaction still remains one of the principal goals of nuclear and hadronic physics. Apart from their intrinsic importance for the study of nuclear forces, NN elastic scattering data are also necessary ingredients in the modelling of meson production and other nuclear reactions at intermediate energies. It therefore goes without saying that all facilities should try to fill in the remaining gaps in our knowledge in the area.

The COSY–EDDA collaboration [6] produced a wealth of data on proton–proton elastic scattering that completely revolutionised the isospin $I = 1$ NN phase-shift analysis up to about 2.1 GeV [11]. However, for proton energies above 1 GeV, very little is known about the $pp$ elastic differential cross-section or analyzing power for center-of-mass angles $10^\circ < \theta_{cm} < 30^\circ$. The cross-section data that do exist seem to fall systematically below the predictions of the SAID partial-wave analysis [11]. In this angular range the fast proton emerging at small angles from a hydrogen target can be measured well in the ANKE magnetic spectrometer, whereas the slow recoil proton emerging at large angles can be measured independently in one of the Silicon Tracking Telescopes. The luminosity that is so crucial for the determination of the absolute cross-sections can be determined using the Schottky method [7] that was mentioned in the previous section. Preliminary data are already available on the differential cross-sections at eight energies and approval has been given to measure the proton analyzing powers at the same energies.

Much greater effort has been made in the study of the spin-dependent terms in large angle neutron–proton scattering. It was pointed out many years ago that the $dp \rightarrow \{pp\}n$ charge exchange at small angles is very sensitive to the spin-spin terms in the $np \rightarrow pn$ amplitude provided the excitation energy $E_{pp}$ in the final $pp$ system is kept

![Figure 3](image_url)

**Figure 3.** Values of the final-state CM momentum $p_f$ (black crosses) and its square (red stars) plotted against the deuteron laboratory momentum $p_d$. The lower panel shows the deviations of the experimental data from the fitted curve in $p_f$.

![Figure 4](image_url)

**Figure 4.** Cartesian deuteron analyzing powers for the $dp \rightarrow \{pp\}n$ reaction for $E_{pp} < 3$ MeV at $T_d = 1.6, 1.8,$ and $2.27$ GeV [16]. The impulse approximation predictions [17] have been evaluated with the SAID amplitudes [11] (solid curves) and also, at the highest energy, when the longitudinal spin-spin amplitude is scaled by a factor of 0.75 (dashed curves).
Under such conditions the $\{pp\}$ state is in a $^1S_0$ state and the charge exchange necessarily involves a spin flip from the initial $np$ spin-triplet of the deuteron. Furthermore, measurements of the deuteron tensor analyzing powers $A_{xx}$ and $A_{yy}$ allow one to distinguish between the contributions from the three spin-spin $np$ amplitudes.

Measurements were carried out at Saclay [13, 14], but only in regions where the $NN$ amplitudes were reasonably well known. These have been extended in fine steps in momentum transfer $q$ to higher energy at ANKE [15, 16]. A cut of $E_{pp} < 3\text{ MeV}$ was typically imposed but any contamination from spin-triplet $P$-waves was taken into account in the theoretical modelling [17]. The ANKE analyzing power results at 1.6, 1.8, and 2.27 GeV are compared in Figure 4 to these impulse approximation predictions using up-to-date $np$ amplitudes [11] as input. The satisfactory agreement at the two lower energies, and also in the values of the differential cross-sections, shows that the theoretical description is adequate here.

Above about 1 GeV neutron–proton data are rather sparse. It comes therefore as no surprise that, when the same approach is employed for the highest energy data shown in Figure 4, the current SAID amplitudes [11] give a poor overall description of the results. However, if the longitudinal spin-spin amplitude is multiplied by a global factor of 0.75, the agreement is much more satisfactory. This is clear evidence that the charge exchange data can provide useful input to the $NN$ database.

Confirmation of these conclusions is to be found in the studies of the deuteron–proton spin correlation parameters measured with the polarized hydrogen gas cell. Results on this are shown in Figure 5. In impulse approximation, these observables are sensitive to the interference between the longitudinal spin-spin amplitude and the two transverse ones. Whereas there is satisfactory agreement with the theoretical predictions at 1.2 GeV, the model is much more satisfactory at 2.27 GeV if the longitudinal input is scaled by a factor of 0.75.

In addition to measuring the spin correlations with the polarized cell, data were also obtained on the proton analyzing power in the $dp \rightarrow \{pp\}_X$ reaction and the results are shown in Figure 6. The message here is very similar to that for the other observables. At 600 MeV per nucleon the SAID input reproduces the experimental points very well but it seems that at 1135 MeV the SAID description of the spin-orbit amplitude has serious deficiencies.

As well as studying the $d \rightarrow p \rightarrow \{pp\}_X$ data to extract the neutron as a missing-mass peak, results were also obtained where $M_x > m_n + m_p$. These events must be associated with pion production, especially through the $\Delta$ isobar.

**Figure 5.** Transverse spin correlation parameters in the $d\vec{p} \rightarrow \{pp\}_X$ reaction at (a) 1.2 and (b) 2.27 GeV [16] compared to the predictions of an impulse approximation model (solid curves). Better agreement is found at the higher energy if the longitudinal input is scaled by a factor of 0.75 (dashed curves).

**Figure 6.** Proton analyzing power in the $dp \rightarrow \{pp\}_X$ reaction at 1.2 GeV (red squares) and 2.27 GeV (blue triangles) [16] compared to impulse approximation predictions. Note that, with the current SAID input [11], the latter almost vanish at the higher energy.
first indications shown in Figure 7 are that the Cartesian analyzing powers are largely opposite in sign to those for \( dp \to \{ pp \} \sigma \) [18]. These data should yield information on the amplitude structure of the \( NN \to N\Delta \) reaction.

**Pion Production in Nucleon–Nucleon Collisions**

One of the priorities at ANKE is to perform a complete set of measurements of \( NN \to \{ pp \} \pi \) at low energy. Since, as mentioned earlier, the \( \{ pp \} \) proton–proton pair is overwhelmingly in the \( 1S_0 \) state, only the polarizations of the initial nucleons have to be studied. As parts of this program, the differential cross-section and analyzing power of the \( \vec{p}p \to \{ pp \} \pi^0 \) reaction were measured at 353 MeV [19] and the same observables measured in quasi-free \( \pi^- \) production on the deuteron, \( \vec{p}d \to p_{sp} \{ pp \} \pi^- \) [20], where \( p_{sp} \) is a “spectator” proton. By making certain theoretical assumptions and retaining amplitudes up to pion \( d^- \) (or higher) waves, the combined data sets are sufficient for a partial-wave decomposition. This is of particular interest for Chiral Perturbation Theory, where it is important to establish that the same short-range \( NN \to NN\pi \) vertex that contributes to \( p^- \) wave pion production is consistent with other intermediate energy phenomena.

For \( \pi^0 \) production, both protons were measured in the ANKE Forward Detector. After selecting the \( 1S_0 \) final state, the kinematics of the \( \vec{p}p \to \{ pp \} \chi \) process could be reconstructed on an event-by-event basis to obtain the \( \pi^0 \) rate from the missing-mass \( M_X \) spectrum. By using a beam with a \( \pm 68\% \) polarization, the cross-section and analyzing power could be measured simultaneously and the results are shown in Figures 8 and 9.

The cross-section data agree quite well over most of the angular range with those taken at CELSIUS [21] and the strong anisotropy is evidence for significant \( d^- \) wave pion production. In the absence of pion \( d^- \) (or higher) waves the

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**Figure 7.** Tensor analyzing powers for the \( \vec{d}p \to \{ pp \} \chi \) reaction at 2.27 GeV as a function of the transverse momentum transfer. The data are integrated over the mass range \( 1.19 < M_X < 1.35 \) GeV/c\(^2\) [18].

**Figure 8.** Differential cross-section for the \( pp \to \{ pp \} \pi^0 \) reaction at 353 MeV. The ANKE measurements (solid black) circles are compared with the CELSIUS data (open red) circles at 360 MeV [21]. The curve is the partial-wave fit.

**Figure 9.** (a) Product of the measured analyzing power and differential cross-section for the \( \vec{p}p \to \{ pp \} \chi^0 \) reaction. (b) Measured values of \( A_y \); the overall systematic uncertainty is \( \pm 5\% \). The curves are partial-wave fits.
analyzing power would vanish and, as seen in Figure 9, this is far from being the case.

In the \( \vec{p}d \to p_0 \{pp\} \pi^- \) experiment, three particles had to be detected in the final state to identify the reaction. In addition to the two protons in the \( ^1S_0 \) state, either the \( \pi^- \) or the third (slow) proton must be measured, the latter in one of the silicon tracking telescopes placed in the target chamber. Together the two detection modes led to a full angular coverage. In either case the slow proton was restricted kinematically to be a spectator so that the cross-section and analyzing power of the quasi-free \( \vec{p}n \to \{pp\} \pi^- \) reaction could be extracted in the \( 353 \pm 20 \) MeV interval, the results being shown in Figures 10 and 11.

The differential cross-section agrees with the earlier TRIUMF measurement [22], except for their two most forward points. The disagreement persists with the analyzing power data measured in the forward hemisphere [23] shown in Figure 11. On the other hand, the agreement with the shape of the cross-section deduced from the \( \pi^- \vec{p}n \to pnn \) reaction [24] is even better.

Even if one considers only \( s, p \), and \( d \)-wave pion production, the cross-section and analyzing power data are insufficient to perform a full amplitude analysis without further assumptions. These were to neglect the coupling between the initial \( ^3P_2 \) and \( ^3F_2 \) waves and to use the Watson theorem to determine the phases of the production amplitudes from these and also the \( ^3P_0 \) wave. There are then seven real parameters available to describe essentially ten features in Figures 8–11. The success achieved here suggests that the phase assumptions are basically correct. The analysis shows that \( d \)-wave production is confined almost purely to the \( ^3P_2 \) channel but by far the largest term is associated with \( p \)-wave production from the initial \( ^3D_1 \) state.

The Future

Although the partial-wave description of the pion production data is both plausible and impressive, one needs to measure other types of observables in order to test its validity. By using a polarized hydrogen gas cell in conjunction with a polarized deuteron beam, it was possible to study the transverse spin-spin correlation in the \( \vec{p}n \to \{pp\} \pi^- \) reaction. The preliminary results [25] are consistent with the predictions of the amplitude analysis discussed earlier. Further checks, which will remove the residual ambiguities, could be made through measurements of the longitudinal-transverse spin correlation but these will require the delivery, installation, and commissioning of a Siberian snake to
rotate the proton spin. This should take place in 2013. The snake will also allow us to study the spin-correlation parameter $A_{00kk}$ in small angle $pp$ elastic scattering.

Although the charge exchange program with a polarized deuteron beam has been very successful, this only allows measurements to be carried out up to 1.15 GeV per nucleon. To go higher at COSY we must work in inverse kinematics and use the polarized deuteron target in conjunction with a proton beam. The charge exchange can then be studied purely through the measurement of two slow protons in the silicon tracking telescopes without using the ANKE magnetic spectrometer at all. However, this opens even more fascinating possibilities, such as the study of $\Delta$ isobar production in $p\Delta \rightarrow \{pp\} \Delta^0$ where the spin alignment of the $\Delta$ isobar can be determined through the measurement of one of the products of the $\Delta \rightarrow p\pi^-$ decay. On the other hand, with its array of detectors, ANKE can investigate simultaneously a wide range of nuclear reactions, which makes the spin program at the facility so exciting.

References

Among all nuclear ground-state properties, atomic masses are highly specific for each particular combination of neutron and proton number, $N$ and $Z$, respectively. The data obtained through mass measurements provide details of the nuclear interaction and thus apply to a variety of physics topics. Some of the most crucial questions to be addressed by mass spectrometry of unstable radionuclides are, on the one hand, nuclear forces and structure, describing phenomena such as the so-called neutron-halos or the evolution of magic numbers when moving towards the borders of nuclear existence. On the other hand, the understanding of the processes of element formation in the Universe poses a challenge and requires an accurate knowledge of nuclear astrophysics. Here, precision atomic mass values of a large number of exotic nuclei participating in nucleosynthesis processes are among the key input data in large-scale reaction network calculations.

Production, Separation, and Cooling of Short-Lived Nuclides

The study and understanding of more and more exotic nuclei and their properties depend to a large extent on the accessibility of these nuclei. Precision mass measurements today are either carried out at low energies with Penning traps, where the beam provided at an energy of some hundreds of eV to tens of keV is usually decelerated for a measurement at only a few eV beam energy. Or mass measurements are performed at higher energies (tens of MeV/u to hundreds of MeV/u) using storage rings. For both approaches to be successful, the isotopes of interest have to be produced in a nuclear reaction, and then prepared prior to their injection into the experimental setup. The exotic nuclei are either produced in an ISOL (Isotope Separation On-Line) or in-flight system. The latter one has the option of adding a gas-filled stopping cell to the system, converting the higher energy beam into a low-energy high phase-space density beam. Most recently, a radioactive fission source (CARIBU, [2]) has been brought on-line, which provides access to exotic isotopes, independent of accelerator use.

In the ISOL method, the 20–60 keV beam undergoes separation by using an isotope dipole magnet separator with a typical resolving power of 2–5,000. This provides a rough isotopic separation, but some isobaric contaminations often remain. Such devices are used for example at the ISOLDE facility at CERN, the ISAC accelerator complex at TRIUMF, or in a similar manner at IGISOL in Jyväskyla. Additional separation can be achieved by using selective ionisation techniques, most noticeably, resonant laser ionisation, which has been used to produce mono-isotopic, typically singly charged ion beams, or even separation of isomeric states. The beam is then transported to a precision mass-
measurement system, which in the case of ISOL production, the method of choice is a Penning-trap system. In order to use the beam most efficiently, and to enhance the reachable precision, the beam is prepared before its injection into the Penning-trap system. This includes cooling, further purification from remaining contaminants, and in some cases, charge breeding to higher charge states. For the cooling, one employs buffer-gas cooling, firstly in a linear Paul trap, where the continuous beam is also converted into bunches, and secondly in a Penning trap. Here, the gas-interaction, in combination with a radio-frequency (RF) excitation at a specific and mass-dependent frequency, leads to a separation of the motion of the stored ions in the trap. The ions of interest, which are resonantly RF excited, can be separated and transferred further, however, the contamination ions remain. This so-called mass-selective buffer-gas cooling technique reaches a resolving power of a few 100,000 and is a notable method to deliver clean mono-isotopic samples to Penning-trap mass measurement systems. Most promising is the use of a multi-reflection time-of-flight mass separator for isobaric purification, which has been successfully demonstrated at the ISOLTRAP experiment [3]. Comparable resolving power and suppression of contaminants can be achieved on time scales an order of magnitude smaller than conventional methods. Similar developments are ongoing at GSI and RIKEN; for an overview see Ref. [4].

In the in-flight method, the isotopes of interest are produced via a heavy-ion reaction at multi-MeV/u energies, and are separated from the co-generated reaction products by using electro-magnetic separators. Examples of such devices include the FRagment Separator (FRS), the Separator of Heavy Ion Products (SHIP) at GSI, the Radioactive-Ion Beam Line (RIBLL2) at IMP in Lanzhou, or the A1900 separator at NSCL at Michigan State University. The magnetic rigidity analysis together with Z²-dependence of the energy loss in specially shaped energy degraders enables separation in flight of isobarically pure samples, which can be transferred further either to a storage ring for mass measurements, like, for example, realized at GSI with the Experimental Storage Ring ESR, or at IMP with the experimental Cooler-Storage Ring CSRe, or to a gas-filled stopper cell. The stopper cell with 0.5 atm of inert and clean buffer gas achieves a fast thermalization of the reaction products typically in a singly or doubly charged state. Electric fields guide the low energy ions to an exit opening, and a low energy beam (few tens to hundreds of eV/u) beam is formed, which can then be delivered to a Penning-trap mass-measurement system, similar to the one at ISOL facilities.

**Penning-Trap Mass Spectrometry**

At low beam energies, Penning-traps provide since many years the necessary means for mass spectrometry on a pure sample of radioactive ions [5]. Only a few tens to a few hundred ions are needed to determine the mass of the isotope of interest with a precision required for addressing many questions in nuclear structure or astrophysics. Penning-trap mass spectrometry exploits the fact that the motion of a trapped particle can be linked to its mass. The technique is based on the single-ion sensitivity as well as on the direct ion detection requiring some few hundreds of milliseconds per measurement cycle. In this way, it is well suited for performing mass measurements on short-lived exotic nuclei with a low production rate.

In a Penning trap, any charged particle is forced onto an orbit unambiguously defined by its mass as well as the magnetic and electrostatic trapping potentials. It is favorable to choose the magnetic field such that the revolution frequency is as high as possible, which immediately effects in a lower uncertainty of the measured quantity. Using the time-of-flight ion-cyclotron-resonance (TOF-ICR) technique, the mass of the isotope of interest can then be extracted in conjunction with a (stable) reference-mass measurement. Radio-frequency fields applied to the electrodes of the Penning trap are used to excite the stored ions and serve for the excitation as well as cleaning purposes as mentioned above. A TOF ion-cyclotron resonance is obtained by scanning the exciting RF field and constitutes a destructive detection method, meaning that the ion is lost from the trap after its measurement.

In the past, Penning-trap mass spectrometry on radioactive ion beams could demonstrate mass measurements reaching half-lives as low as t₁/₂ = 8.6 ms in the case of ¹¹⁵⁵Bi [7], where the half-life of the ground (isomeric) state is t₁/₂ = 183 s (t₁/₂ = 87 s) [7]. Until today, relative mass uncertainties below 10⁻⁹ could only be demonstrated on stable nuclides [8]. For short-lived nuclides, the phase-imaging ion-cyclotron-resonance technique (PI-ICR) has been introduced at SHIPTRAP demonstrating resolving powers beyond 10⁸ [9]. Its application to radioactive beam will constitute a breakthrough with respect to achievable resolving power and precision on short-lived species.

**Storage-Ring Mass Spectrometry**

Heavy-ion storage rings turned out to be flexible instruments for studies on exotic nuclei at high energies. Prominent examples are the measurements of nuclear masses [10] and decays of highly charged ions [11].
Storage-ring mass spectrometry is based on the accurate determinations of the revolution frequencies of stored ions, provided the effect of the large velocity spread due to nuclear reaction is made negligible. The latter can be done in two ways, namely by beam cooling or by tuning the ring into the so-called isochronous ion-optical mode. While the cooling requires a few seconds and can thus be applied to nuclei with lifetimes in the same order or longer, no further manipulations on the beam are needed in the latter technique which makes it well-suited for investigations of very short-lived nuclei. In both methods, a broad range of different nuclear species is stored. Frequency measurement is performed by non-destructive Schottky pickups or by dedicated time-of-flight (TOF) detectors. Two storage ring facilities pursue mass measurements of exotic nuclei. These are the ESR in Darmstadt and CSRe in Lanzhou.

The striking advantage of the storage-ring mass spectrometry is that the frequency determination, and correspondingly the mass measurement, can be achieved on the basis of a single stored particle, which allows reaching the very exotic nuclei with smallest production rates of well below one stored particle per day. For instance, the mass of \(^{208}\text{Hg}\) nuclide was measured to an accuracy of 30 keV from a single hydrogen-like ion stored once in the ESR in a two-week long experiment [12]. Furthermore, several new isotopes and isomers have been discovered in the ESR in the last years [13].

In addition to the highest possible sensitivity, storage-ring mass spectrometry can access nuclei in a very broad range of half-lives. Thus, a novel resonant Schottky detector [14] has been commissioned recently in the ESR, which enabled frequency measurements on single ions within merely 10 ms. Applying the TOF detector in the isochronous mode of the ring allows for frequency determination within about 20 revolutions, which corresponds to about 10 us. The latter is the anticipated lower half-life limit for nuclides accessible with this technique, though not demonstrated yet. The 4.66 MeV isomeric state in \(^{133}\text{Sb}\) with \(t_{1/2} = 17\) us in neutral atoms was observed in the ESR. However, in fully ionized nuclei, as they were stored in the ESR, the half-life should be much longer since the internal conversion decay is disabled [15].

**Precision Masses in Nuclear Physics and Astrophysics**

*Halo Nuclei*

Halo nuclei, both neutron and proton, have fascinated the nuclear physics community for over 25 years now, and still spur active interest, perhaps more than ever before, due to significant advances on the theoretical and experimental frontiers. Halo nuclei represent ideal study objects from a theoretical perspective as they are few body systems that can be tackled with *ab-initio* methods, but—due to their extreme neutron-to-proton ratio (He-8 has a ratio of \(N/Z = 3\)—provide challenges to the standard approaches. Moreover, the theoretical predictions can now be compared to precision data, such as ground state binding energies or neutron- and proton-separation energies. What had been difficult before the advent of Penning traps was to reach the required precision and accuracy for mass determination for these isotopes near (or beyond) the drip-lines.

Figure 1 shows the known or expected halo nuclei and where precision mass measurements were conducted. What enabled those measurements at Penning traps was firstly the availability of high-quality beams, for example from ISOLDE and ISAC, but most importantly the speed and sensitivity of the mass-measurement systems. In the case of \(^{11}\text{Li}\), for example, still a sub-keV precision could be reached in spite of the short half-life [6]. Similarly, the mass measurements of the neutron-deficient neon isotopes at ISOLTRAP represented a significant challenge due to the limited production and short half-lives of around 100 ms. Yet, the ISOLTRAP results, as shown in Figure 2 (taken from Ref. [16]), show excellent agreement with the two-neutron separation energies \(S_{2n}\) from the Fermionic Molecular Dynamics model calculations, where the oxygen core is well represented. This, together with laser spectroscopy data identified \(^{17}\text{Ne}\) as a one-proton halo nucleus.

![Figure 1. Section of the Segre chart up to Z = 10. Indicated are the identified and expected neutron and proton halo nuclei. Different labels show where precision mass measurements have been carried out (adapted from B. Jonson, Phys. Rep., 389 (2004) 1).](image-url)
3N-Forces

Sophisticated tools based on quantum chromodynamics have brought a renaissance to nuclear-structure theory to study the complex nuclear interaction with all its effective forces, and the resulting nuclear structure. In order to test the predictive power of these models, theoretical values of nucleon separation energies can be compared to experimental results. Highlights in this respect have been the Penning-trap mass measurements of $^{51,52}$Ca with the TITAN experiment [17] and most recently of $^{53,54}$Ca with the ISOLTRAP experiment [18]. Large deviations from the values of the previous Atomic-Mass Evaluation AME2003 [19] and a strong change in the general trend of the $S_{2n}$ values were found. The TITAN results as well as theoretical predictions, which include microscopic valence-shell calculations with three-nucleon forces (NN+3N) from chiral effective field theory, are compared in Figure 3. The outstanding agreement demonstrates that the description of nuclei with extreme neutron-to-proton ratios is closely connected to a deeper understanding of nuclear forces.

Test of the Isobaric-Multiplet Mass Equation in pf-Shell Nuclei

The Isobaric-Multiplet Mass Equation (IMME) follows from the assumption of the two-body nature for any charge-dependent effects and the Coulomb force between the nucleons [20]. IMME connects masses of $2T+l$ members of an isobaric multiplet and—if the isospin symmetry holds—has to have a parabolic form. If, however, a deviation to the quadratic form is observed this could lead to new physics like, for example, enhanced effects of isospin mixing and/ or charge-dependent nuclear forces. A possible deviation to the quadratic form can be described by adding a cubic term with a coefficient $d$.

Numerous tests of the validity of IMME in light nuclei have been performed in the last years based nearly entirely on the precision mass data obtained with Penning traps (see Ref. [21] and references cited therein). Except for slight disagreements at $A = 8, 9, 32,$ and 33 the data are well described by the quadratic form of IMME. However, the first ever test of IMME in heavier, pf-shell nuclei broad a surprise. Masses of neutron-deficient $^{58}$Ni projectile fragments have been measured at CSRz [22]. With new masses for $^{41}$Ti, $^{45}$Cr, $^{49}$Fe, and $^{53}$Ni nuclei, data for four isobaric quartets became complete. Figure 4 illustrates the determined $d$-coefficients. A 3.5σ deviation for mass number $A = 53$ is striking. State-of-the-art theoretical calculations cannot reproduce the obtained result, and—if this deviation is confirmed in further precision studies—it will provide us new insights into the nature of nuclear forces.

rp- and r-Process Studies

The chemical elements have been created as a result of nuclear processes in stars and stellar explosions. Up to iron-56, the nucleus with the highest binding energy per nucleon, new elements can be created by fusion reactions in stars. X-ray bursters, thermonuclear explosions in the Universe, are thought to be powered by the rapid proton-capture process (rp-process) on highly neutron-deficient, exotic nuclei. In a stellar binary system of a neutron star can accrete matter
from a companion star. Hydrogen-rich matter accumulates on the surface of the neutron star resulting in an explosion after the system becomes unstable [23]. Astronomical observations of minute-long burst tails could be explained by a considerable slowdown of the rp-process in the A = 64–72 region. Moving along the proton drip-line, the rp-process encounters the exceptionally long-lived positron emitters $^{64}$Ge, $^{68}$Se, and $^{72}$Kr. Previous experiments could show that $^{68}$Se and $^{72}$Kr are indeed located at the proton drip-line. They were thus identified as waiting points in the rp-process because they cannot be bypassed and the process has to “wait” until they decay by the slow positron emission [24]. On the contrary, the recent mass measurement of $^{65}$As in the CSRe provided evidence that $^{64}$Ge is not a major waiting point in the rp-process for the majority of relevant temperature-density conditions in X-ray bursts [25]. Based on the mass measurement of $^{45}$Cr, performed also in the CSRe, a formation of a strong Ca-Sc cycle in the rp-process can basically be excluded [26]. Thus, the precise mass values are reliable input for the calculation of possible rp-process paths using nuclear reaction networks [27].

The rapid neutron-capture process (r-process) of stellar nucleosynthesis is considered to be responsible for the production of the heavy elements. However, the astrophysical site has not been identified yet. The r-process path depends strongly on the employed astrophysical model and the supposed stellar environment. Different temperature and density conditions reflect in slightly different pathways of the r-process. Nevertheless, the underlying structure of nuclei plays its role also in stellar environments, making nuclei around the closed neutron shells $N = 50$ and $N = 82$ prominently appear. Penning-trap mass measurements have reached the r-process path for nuclides around $^{80}$Zn$_{50}$ and $^{132}$Sn$_{82}$ [28, 33], which can constrain nuclear mass models that in turn are needed as input for astrophysical models whenever experimental masses are not (yet) available. Accurate mass measurements are also needed to reliably compare the calculated r-process abundances to observations.

A possible theory, alternative to the supernova-induced r-process, is the decompression of neutron-star matter by its merger with another neutron star. In the neutron-star crust, exotic rare isotopes transform into the so-called equilibrium nuclei and contribute to the elemental abundance. A recent example is the mass measurement of $^{82}$Zn, which is important for modeling the crustal composition of neutron stars [3].

As an example, Figure 5 shows the change in the sequence of nuclides for the model calculations with MSk7 Skyrme [34, 35] force mapped along the chart of nuclides. Nuclides measured by ISOLTRAP are marked by blue squares, the black crosses denote the AME2012 data base [29]. The new sequence including the ISOLTRAP mass value of $^{82}$Zn is depicted by the red dashed line. It can also be seen from this plot that the last nucleus in the outer crust, that is, before neutrons start to drip out, is located on the respective drip-line of the considered model. Calculations with the MSk7 force exhibit a change in the sequence of nuclides around a density of $7 \times 10^{10}$ g/cm$^3$. Note, that also in a neutron-star environment, the magic neutron shells $N = 50$ and $N = 82$ are a dominating effect of nuclear structure to persist. Through the precise mass value from a Penning-trap measurement and by testing 25 different mass models it was possible to establish that $^{82}$Zn is not present in the outer crust of a neutron star [30].

**Summary and Outlook**

In recent times, the high-precision Penning-trap and storage-ring mass measurements have reached a new quality in respect to accuracy, sensitivity and applicability. This is
among others based on novel developments in ion cooling, preparation and detection systems. Furthermore, as the examples given above demonstrate, the field of nuclear structure and astrophysics is revolutionized due to new beams of short-lived radionuclides that can now be produced in laboratories around the world. The success of these techniques and the numerous applications of precision mass data result in the fact that all new and upgrading radioactive beam facilities have active or planned programs for precision mass spectrometry. These are among others the MATS [31] and ILIMA [32] projects at FAIR or DESIR at SPIRAL2.

Acknowledgment

The authors express their gratitude to all colleagues within the field of high-precision mass spectrometry on short-lived nuclides. We thank M. Hempel for providing Figure 5. This work is partly supported by the Max-Planck Society, by the Helmholtz association through the Nuclear Astrophysics Virtual Institute (VH-VI-417/NAVI), by the Helmholtz-CAS Joint Research Group (HCJRG-108).

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In 2012 the new collinear resonance ionization spectroscopy (CRIS) experiment at ISOLDE celebrated its first successful campaign on the rare francium isotopes. This work builds on 30 years of research and development that has aimed at combining the high sensitivity of resonance ionization spectroscopy with the high resolution of collinear laser spectroscopy.

It took more than a decade from the first demonstration of the laser by the group of Professor Townes to the realization of the first high resolution laser spectroscopy experiment [1]. This seminal work developed a widely tunable laser with a sufficiently narrow line width to resolve the hyperfine structure of $^{23}$Na. This structure results from the coupling of nuclear and electronic angular momenta in a single atomic level, which is non-degenerate if the nucleus has a non-zero magnetic dipole or electric quadrupole moment. Within four years of this breakthrough laser spectroscopy techniques were being developed to study exotic isotopes at accelerator laboratories [2]. Compared with previous optical spectroscopy and atomic-beam-magnetic-resonance techniques the new method of laser spectroscopy represented a paradigm shift in terms of sensitivity. This opened up the possibility of extending measurements on the properties of the nuclear ground state to short-lived nuclei produced at radioactive beam facilities. In the last 40 years, a variety of laser spectroscopy techniques has been developed, reflecting the differing demands placed on the experimentalist by a particular element of interest. However, two dominant techniques have emerged for studying short-lived exotic isotopes: in-source measurement and collinear-beams laser spectroscopy [3, 4]. In-source laser spectroscopy uses multiple laser beams of selected wavelengths to resonantly stepwise excite a radioactive atom to the ionization continuum within the target-ion source. Tuning the frequency of one of the lasers as the ion yield is monitored enables the atomic hyperfine structure and isotope shift to be measured. In-source laser spectroscopy is highly sensitive and able to measure rare isotopes produced at rates of less than one atom per second [5]. This is due to the high efficiency of the resonant ionization process (which can exceed 10%) and the high detection efficiency of ions with charge particle detectors. The obtainable resolution with in-source laser spectroscopy is limited by the broadening associated with the conditions of the ion-source, such as high temperature or high gas pressure (in gas cell work), which is typically between 1–4 GHz depending on the characteristics of the source. Collinear laser spectroscopy reduces the broadening associated with the initial conditions of the target ion source by overlapping the laser with an accelerated ion (or atom) beam. The reduction in broadening is due to the conservation of the energy spread under acceleration, which at 50 keV will be less than 10 MHz. In its simplest incarnation collinear laser spectroscopy detects resonantly scattered photons (fluorescence) following the atomic excitation by the laser light with a photomultiplier tube. Collinear laser spectroscopy also has the flexibility to study transitions in the ion or the atom, with the introduction of an alkali-metal filled neutralization cell. While this method has a high resolution it has a low sensitivity compared to in-source spectroscopy due to the low efficiency associated with detecting the scattered photons and the high background as-
facilities and methods

associated with non-resonantly scattered light, limiting its application to isotopes produced with yields greater than $10^6$ atoms/s. Building on the basic geometry of collinear laser spectroscopy there are many alternative techniques that utilize particle detection or ion bunching methods to reduce the background or improve the sensitivity of the technique, allowing isotopes produced with yields down to $10^2$ atoms/s to be studied [4, 6, 7].

The collinear resonance ionization spectroscopy technique was first suggested in 1982 by Kudryavtsev and Letokhov [8] as a method for searching for rare isotopes with natural abundances of less than $10^{-10}$. By using multi-photon ionization on atoms collinearly overlapped by several laser beams, the technique promised to combine the high sensitivity of in-source spectroscopy with the high resolution of collinear laser spectroscopy. Such a sensitive technique had an obvious application at on-line facilities to study exotic isotopes with low production rates. In 1984 the group led by Professor Letokhov proposed a new collaboration with Professor Otten’s group from Mainz to develop the technique at ISOLDE. The first radioactive results were obtained in 1988, where the experiment demonstrated a high element selectivity and background suppression, which was able to reject high isobaric contamination. The overall detection efficiency was 0.002% and no better than fluorescence detection [9].

The low efficiency was due to the loss associated with the duty cycle of the pulsed lasers used to ionize a continuous atom beam and the low population through neutralization of the metastable atomic state used in the ionization process. This initial campaign highlighted that a bunched ion beam that matches the duty cycle of the pulsed lasers is essential for the efficient application of the CRIS technique.

The development and installation of a RFQ linear Paul trap at the IGI-SOL facility in Jyväskylä [10] provided the necessary bunched ion beam for tests of the CRIS technique to be performed with the collinear experiment operated by the Birmingham–Jyväskylä–Manchester collaboration [11]. This work was performed on $^{27}$Al and demonstrated an efficiency of ~3%, an improvement by almost three orders of magnitude. These initial tests also underlined the need for ultra-high vacuum (UHV) in the laser–atom interaction region to avoid collisional ionization with the residual gas molecules, the main source of background in the CRIS technique. The introduction of a similar ion buncher (ISCOOL) in 2008 at ISOLDE [12] made it possible to again propose a CRIS based experiment with a new beam-line that can operate under UHV conditions ($<1 \times 10^{-8}$ mbar) [13].

The period of 2008 and 2009 saw the design, construction, and installation of all the major components of the experiment (Figures 1 and 2 [14]). By the end of 2009 the beam-line was under vacuum and the ability to operate the charge exchange cell while maintaining UHV within the interaction had been demonstrated [14]. In 2010 and 2011 the first radioactive beams were delivered and transported through the experiment and the initial resonant signal was observed in $^{207}$Fr [15] (Figure 3). These initial commissioning tests were used to optimize the detection setup, neutralization efficiency, stability of the beam-line and data acquisition system. In 2012 this experience was utilized in two on-line experiments that measured the magnetic moments and charge radii in nine isotopes and five isomers of francium ($^{202-206,218,219,229,231}$Fr) for the first time. In collaboration with

![Figure 2. Top view of the CRIS experimental beam-line at ISOLDE. The radioactive beam enters from the right-hand side and overlapped with the laser beam in the straight section. Resonant ions are deflected through 20 degrees and detected with an MCP located on the left-hand side of the photograph.](image)
The ISOLDE RILIS team used a narrow bandwidth pulsed Ti:sapphire laser (<1 GHz) to excite the ground state of francium to the $8p_{3/2}$ state, and thereby measure the hyperfine structure as the frequency of this laser was scanned. A second high power laser was used to ionize the excited state. This work demonstrated a non-resonant ionization efficiency of less than 0.001%, which leads to almost background free spectra for rare isotopes (in the absence of isobaric contamination of other elements). The ratio of the experimental efficiency to the non-resonant ionization efficiency is approximately the degree by which the CRIS experiment can separate nuclear isomeric states from the ground state. The ability of the CRIS experiment to purify beams and separate isomeric states was also demonstrated in the 2012 experimental campaign, where the isomeric states in $^{202,204}$Fr were individually ionized and delivered to a recently commissioned UHV-compatible alpha-decay spectroscopy station [17–18].

The first long shutdown of the LHC era has now started at CERN, which is being used by all experiments as a period of upgrade and optimization. The CRIS experiment will use this opportunity to further reduce the pressure within the vacuum chambers and optimize the beam diagnostics within the apparatus. New experimental campaigns are planned for 2014 to study the neutron rich copper isotopes (approaching the $N = 50$ shell closure) as well as performing high resolution measurements on polonium to refine the quadrupole moments and measure the spins. An extension of the francium campaign to the $^{201m.g}$Fr and $^{203n}$Fr as well as the newly discovered $^{233}$Fr isotope will also be carried out.

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The Status of CNAO at the Beginning of 2013: The Clinical Trials

The CNAO and the Rationale for Hadrontherapy

The CNAO (Italian acronym that stands for National Centre for Oncological Hadrontherapy) began its clinical activity in September 2011 with the launch of the experimental treatments with beams of protons. In November 2012 the first patient was treated with carbon ions. On both occasions it was an absolute novelty in the panorama of Italian healthcare.

The therapeutic capacity of hadrontherapy is linked to the physics-radiobiological features of hadrons in relation to dose deposition in tumour tissues. Hadrons release most of their dose in a narrow band, the Bragg peak, which can be appropriately varied in its depth according to the energy used and in its amplitude based on the superposition of multiple peaks with different energy, so as to focus the disruptive effect only on tumor cells. It follows that, with equal distribution of the dose to the target, the integral dose to healthy tissues is much lower than the one supplied with X-rays and it is therefore possible to perform conformational treatments also near critical structures. In the case of carbon ions an increased effectiveness of radiation adds up, related to the considerable density of damage that is produced in the tumor. The carbon ion then becomes a “surgery” instrument to sterilize radioresistant and normally non-oxygenated tumors that little react to conventional techniques.

The scientific validity of hadrontherapy is by now demonstrated by the important clinical development in this technique that is practiced in several dozen hospitals around the world and representing a booming market. More than 90,000 patients have been treated so far with beams of protons, and there are 35 protontherapy hospital centers and 20 others will be operational in the next 3–5 years. The application of carbon ions is more recent and limited, but with great curing perspectives for difficult diseases and currently not treated with effectiveness, five centers are operational in the world and CNAO is the second in Europe and in the Western world. Until now about 9,000 patients have been treated with carbon ions. The scientific interest of hadrontherapy is also confirmed by the impulse that the European Community has placed on this therapy, supporting with relevant funds various initiatives within the framework of training, technological development, and research.

Clinical appropriateness of the use of hadrons with respect to diseases is shown in a systematic manner using data from literature, pathology by pathology, to illustrate applications of both beams of protons and carbon ions. There are several international-level estimates on the number of potentially eligible patients for treatment with hadrons. Considering Italy as example (about 60 million inhabitants), of the over 120,000 Italian patients who each year receive the conventional radiotherapy, about a 1,000 patients are considered high-priority to receive a treatment with protons, and about 1,500 to carbon ions. In addition to this number, a further 15,000 are to be considered eligible patients with a potential benefit, but not completely demonstrated by clinical evidence available today. Patients affected by “high-priority” pathologies, as reported in Table 1, have been chosen for the clinical trials ongoing at CNAO.

In relation to economic consistency, it should be underlined that treatments with carbon ions apply to reducing the number of sessions (hypo-fractionation) by virtue of the superior radiobiological effectiveness of these radiations. It also follows a reduction of direct costs of healthcare, that concern both the patient and any accompanying persons, for expenses related to long travels. Similarly, the hypo-fractionation brings benefits in indirect costs, not of healthcare nature; in fact, patient and accompanying persons benefit of the overall reduction of the treatment period because they can go back earlier to their normal life and restart their usual economic activity earlier. Finally, hadrontherapy represent a painless treatment, little invasive and generally well tolerated by patients, which constitutes a further cost reduction that one can define as intangible and that is related to a better quality of life for patients.

The Clinical Trials at CNAO

With the inauguration of CNAO, on 15 February 2010, the phase of the construction of the Centre ended and the second phase, of the so-called clinical trials, started. This phase has taken place across the years 2010–2013 and will allow to scientifically validating hadrontherapy applied to the cure of many clinical protocols. It will also lay the groundwork for the subsequent phase of start-up at full operation rhythm of the structure that intends to treat, under outpatient treatment, a few thousand patients per year, expanding more and more the clinical indications and bringing forward clinical, radiobiological, and translational research.
Clinical results of the first protocol (CNAO 01/2011 v. 2.0) about treatments with protons of 30 patients affected by chordomas and chondrosarcomas of the skull base, were transmitted in February 2013 to the Istituto Superiore di Sanità. All treatments carried out took place in accordance to the Protocol both in terms of duration of therapy and in terms of dose limits for organs at risk and of target volumes covering.

The study was intended to evaluate the following primary goals: (1) acute toxicity, during ongoing treatment and detectable within 90 days and (2) local response within 90 days. Concerning objective 1, for the success of the study it was required that no more than 3 patients out of 30 showed G3 toxicity at 90 days to the therapy completion. Moreover, it was required that no more than 2 out of 30 patients showed G4 toxicity during therapy and in the following 90 days. The results showed that no patient presents G3 or G4 toxicity.

With regard to objective 2, for the success of the study it was required that no more than 5 out of 30 patients showed disease progression within 90 days after the end of therapy. All patients have reported disease stability upon re-evaluation using MRI 3 months after the end of the radiant treatment. Given the positive results thus obtained, the CNAO Foundation goal is to obtain the CE marking of the first Protocol by early 2013. Later the certificates of the other protocols will gradually add up while the treatments of patients foreseen by the studies will be completed.

### Introduction to CNAO Features

The Centre, shown in Figure 1 [1], is placed in an area of Pavia that hosts other hospitals and the University campus, thus allowing the creation of synergies and collaborations. The real-
ization of CNAO, whose main clinical parameters are summarized in Table 2, and its future activities are based on a strong collaboration network (presented in detail on the website: http://www.cnao.it) that links the Foundation with the most important institutions dealing with research and clinical applications, in Italy and abroad. CNAO is part of ENLIGHT (European Network for Light Ion Therapy) and within the 7th Framework Programme of the European Community, CNAO coordinates the project ULICE (Union of Light Ion Centres in Europe), in which twenty European institutes collaborate to “open” hadrontherapy centers to the international clinical and scientific community and to support research, training, and networking.

In 2013 a program for the design of a dedicated experimental beamline has been launched. Within three years a research-dedicated facility for radiobiology, detector developments, clinical research, and translational research will become operative at CNAO.

Acknowledgment
The author is deeply grateful to all the people of the CNAO Collaboration who have worked and are still contributing to the success of the CNAO project.

Reference

S. ROSSI
CNAO Foundation

Table 2. Main clinical parameters of the CNAO facility.

<table>
<thead>
<tr>
<th>Beam particle species</th>
<th>p, C⁶⁺, possibly He²⁺, Li³⁺, Be⁴⁺, B⁵⁺, (O⁸⁺)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam range</td>
<td>from 3 g/cm² to 27 g/cm²</td>
</tr>
<tr>
<td>Average dose rate</td>
<td>2 Gy/min (for treatment volumes of 1,000 cm³)</td>
</tr>
<tr>
<td>Dose delivery system</td>
<td>Active scanning</td>
</tr>
<tr>
<td>Beam size at isocenter</td>
<td>4 to 10 mm FWHM for each direction independently</td>
</tr>
<tr>
<td>Dose delivery precision</td>
<td>≤ ± 2.5%</td>
</tr>
<tr>
<td>Field size at isocenter</td>
<td>5 mm to 34 mm (diameter for ocular treatments) and 2 x 2 cm² to 20 x 20 cm² (for H and V fixed beams)</td>
</tr>
</tbody>
</table>
Accelerator Production of Medical Radionuclides: A Review

Background

Almost from the beginning of the discovery of radioactivity researchers began looking for ways to create new elements and/or isotopes of those elements. Initially those attempts centred on making use of the alpha particles emitted from natural radioactivity as with Rutherford’s demonstration of the $^{14}$N($\alpha$,p)$^{17}$O reaction [1]. Soon this escalated to the use of electrostatic devices to impart high energy to protons, deuterons, and alpha particles.

With the invention of the cyclotron by Ernest Lawrence, the possibilities for artificial radionuclides began to expand rapidly. Many of those newly discovered radioisotopes were tried in medicine, recognizing the possibility that the energetic decay species could be used to kill cancer cells.

This review explores some of the advances in cyclotron applications to medicine made over the last eight decades with specific examples to illustrate the impacts made.

1930

Following Lawrence's success with his first cyclotron, plans were made for successively larger devices to produce higher and higher energies. With the 37-inch cyclotron he and his colleagues managed to produce a number of artificial isotopes as well as the production of elements not easily found in nature (C-11, C-14, I-131, and astatine and technetium; extracted by Segre from a molybdenum beam stop sent to him by the Berkeley group).

Lawrence’s brother John joined the Berkeley group and conducted the first medical therapeutic experiments using P-32 to treat leukemia [2]. He went on to use other cyclotron radioisotopes such as Na-24, Fe-59, and I-131 in medical experiments.

1940

The first cyclotron dedicated to medical applications was installed at Washington University, St. Louis in 1941, where radioactive isotopes of phosphorus, iron, arsenic, and sulphur were produced.

With the development of nuclear fission and the focus on creating a nuclear bomb for use in the Second World War by using the cyclotron concept to produce the isotopes needed through electromagnetic separation, cyclotron isotope production research stalled. After the war, with the availability of reactors the focus for radioisotope production shifted to the use of the neutron capture reaction. This approach was obvious since the flux of neutrons produced in the new research reactors made it possible to produce very large quantities of certain radionuclides in a relatively short time.

The one short coming in using the (n,$\gamma$) reaction is that the final product is inherently low specific activity, that is, the target and product have the same proton number (same element). The low specific activity of these radiotracers would limit their use in some biological studies.

1950

In the interim years following the War, the focus on radionuclide production had shifted to reactors with their multipurpose capabilities and ease of production through the high flux of neutrons. However the production of radionuclides using cyclotrons for medical applications gained new interest in the 1950s, due in large part to the discovery that $^{201}$Tl could be used as an analog of potassium ions and could, therefore, be used as a tracer for detecting myocardial perfusion. Thallous chloride labeled with $^{201}$Tl remains an important diagnostic tool for measuring cardiac blood flow despite the availability of $^{99m}$Tc myocardial perfusion agents. This became even more evident during the shutdown of two major producers of $^{99m}$Tc during the 2009 medical isotope crisis.

Nevertheless, at least two centers built dedicated cyclotrons in medical facilities, at the Hammersmith Hospital in London, UK and at the Washington University Medical School in St. Louis, MO, USA.

1960

Throughout the 1960s, cyclotron-based production of radionuclides relied on machines in physics departments where the multiparticle devices explored nuclear properties at low energies.

Fundamental studies in hot atom chemistry dominated the research agenda. Hot atom chemistry is where the nucleogenic atoms have sufficient energy to interact with the chemical (elements or compounds) to form new chemical species. Most of the work centered on reaction of C-11, N-13, and F-18 [3]. Much of this effort laid the foundation for the radiochemistry used in positron emission tomography (PET) over the next few decades.
1970

The Hammersmith group in London provided the tools for dealing with radioactive gases in a comprehensive and efficient manner that became the backbone of radionuclide production for the last several decades [4].

This trend continued through the 1970s until late in the decade when the Wolf group at Brookhaven National Lab in the United States measured the proton cross-sections for the light positron emitters for oxygen, carbon, nitrogen, and fluorine demonstrating that these positron emitters could be produced in large quantities at low energy and with only a proton cyclotron obviating the need for multiparticle cyclotrons [5].

Table 1 (and Ref. [6–12] therein) provides a list of nuclear reactions used to produce the conventional low z PET nuclides using the standard methods and those that made use of (p,n) reactions at low proton energy.

Typical energies for the maximal cross-sections for these reactions were in the 7–15 MeV range. Thus low energy proton cyclotrons could be used to produce large quantities of these radionuclides.

In the late 1970s The Cyclotron Corporation (TCC, Berkeley, CA) designed negative ion cyclotrons that accelerated H-ions and used a stripper foil to extract the protons at the desired energy. The stripper foil removes the electrons bound in the hydrogen ion, creating a positively charged proton that subsequently rotates in the reverse direction and can be directed out of the cyclotron. The radius of extraction dictates the energy of the proton beam. In addition, the negative ion circulating in the cyclotron allows for the simultaneous extraction (stripping) of multiple beams of varying energy and intensity. These cyclotrons become extremely flexible in terms of the beams delivered.

The TCC cyclotrons had a maximum energy of 42–45 MeV and were designed to produce large quantities of radionuclides for SPECT, such as Tl-201, Ga-67, and In-111. They were also to be used to generate neutrons for neutron therapy by bombarding Beryllium targets with the protons at 45 MeV. Scandatronix™ in Sweden followed suit with their MC series of cyclotrons.

1980

The ability to extract multiple beams simultaneously allowed CTI, Incorporated (CTI brought the TCC assets of TCC when TCC became bankrupt in the early 1980s) to take the bold step of designing a cyclotron making use of protons only. It became the benchmark for all future cyclotrons designed to produce PET nuclides. The studies from the Wolf group at BNL confirmed that a proton-only machine could produce not only adequate quantities of the standard PET radionuclides but in many cases larger amounts than what were available from the traditional routes [13].

However for this approach to work a number of targetry issues had to be overcome. As seen in Table 1, O-15 and F-18 required the use of highly enriched isotopes. The first breakthrough was a combination of developing a practical O-18 target based on enriched O-18 water plus the development of a rapid synthesis of 18F-fluorodeoxyglucose (FDG) from the produced 18F-fluoride [14].

While FDG was initially developed for brain research using PET [15] it became apparent early on that FDG could be used in monitoring cardiac function and cancer [16].

Research in the use of PET for assessing function on a cellular level grew rapidly through the 1980s with the ability to make high specific activity C-11 tracers to enable neuroscientists to study receptors in the brain as a function of disease and to monitor changes in these systems through therapeutic treatment [17].

Once the use of FDG for detecting early cancer became apparent, the first truly clinical studies became possible and now the Nuclear Medicine community had a new tool that would drive the field over the next few decades.

1990

In the late 1980s the U.S. Department of Defense supported research and development of new accelerators based on the Star Wars technology. There were three funded projects, all of which were based on the use of linear accelerators. The aim was to make use of the technology, which could produce a very high density of particle beams of low energy. These new ac-

Table 1. Standard PET radionuclides with relevant production parameters.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Standard reactions</th>
<th>Proton reactions</th>
<th>Natural abundance (%) of target</th>
<th>Minimum energy (MeV)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>11C</td>
<td>14N(p,α) [6]</td>
<td>14N(p,α)</td>
<td>14N – 99.6</td>
<td>7–8</td>
</tr>
<tr>
<td>13N</td>
<td>16O(p,α) [7]</td>
<td>13C(p,n) [8]</td>
<td>13C – 1.1</td>
<td>5</td>
</tr>
<tr>
<td>15O</td>
<td>14N(d,n) [9]</td>
<td>15N(p,n) [10]</td>
<td>15N – 0.4</td>
<td>7</td>
</tr>
<tr>
<td>18F</td>
<td>20Ne(d,α) [11]</td>
<td>18O(p,n) [12]</td>
<td>18O – 0.2</td>
<td>6–7</td>
</tr>
</tbody>
</table>

†This is the minimum energy for protons to make useful quantities of the radionuclide.
accelerators were to compensate for the low production cross-sections at low particle energy (<10 MeV) with the increased beam current (100–1,000 µA). While the accelerator technology had advanced to achieve the requisite beam currents the target technology had not been tried under these severe conditions (kilowatts deposited in small volumes of liquids or gases) [18].

Science Applications International Corporation, San Diego, CA planned to build an 8 MeV 3He++ radio frequency (RFQ) accelerator. Its unique features included simplicity in design and operation with low neutron field from the accelerator (no inherent neutrons from the accelerating particle or the nuclear reactions to be utilized—3He,4He and 3He,p]. The as built machine had a projectile energy of 10 MeV [19].

AccSys Technology Incorporated, Pleasanton, CA, proposed a Linac, also powered by RFQ, but accelerating protons. A variety of energies could be achieved by varying the length of the accelerator (adding on additional accelerating cavities) [20].

Science Research Laboratory Inc., Somerville, MA, proposed a 3–4 MeV Tandem Cascade Accelerator (TCA) that would accelerate deuterons for 15O production (14N(d,p)15O reaction) and protons for 18F production (18O(p,n)18F reaction). The TCA is an electrostatic accelerator that starts with negative ions that pass through an electron stripper to convert to positive ions that doubles the energy for the same potential difference [21].

At the same time IBA built a 3 MeV D+ cyclotron dedicated to the production of 15O. While not part of the Star Wars effort, IBA recognized the potential advantages of a low cost, low energy device. Several of these small cyclotrons were situated in Europe. Of the Star Wars machines only the TCA was built, installed, and operated on a routine basis to produce radioisotopes for PET (15O production at Mallinckrodt Institute of Radiology at Washington University in St. Louis). The scientist associated with this effort formed a new company, Newton Scientific, Incorporated, and is still building low energy accelerators, none of which have been purchased for radioisotope production.

The other proposed machines were built and tested at various locations. However, only AccSys has been installed and used routinely in a hospital setting. Nonetheless, the gridded gas target window concept was utilized with 3He++, RFQ and shown to work for beam currents of ~70 µs pulses at 360 Hz with a peak current of 3–5 mA, about 2.5% duty cycle, and an average current of 75 µA on Arnavar windows of 7.6 µm thickness.

2000

The major suppliers of low energy cyclotrons became entrenched with their products where more than 600 devices now populate the world. The power of these cyclotrons has continuously increased as the demand for tracers has increased. The external ion sources have played a significant role in the development of higher powered cyclotrons. This technology was used by TRIUMF in their 500 MeV program and adapted first by IBA for its 30 MeV cyclotron and later by EBCO (now Advanced Cyclotron Systems, Incorporated, ACSI) for their products. Other cyclotron manufacturers around the world have followed suit.

With respect to advances in the imaging world, increased interest in developing non-traditional positron emitting radionuclides has resulted in the use of radiometals such as Cu-64 and more recently Zr-89. These radionuclides are produced by using metallic targets which can typically stand-up to higher beam currents. Because of the longer half lives (e.g., Cu-64, 12.4 h) these radiometals are often produced at a few research centers and shared amongst other centers. The volume of use has not reached the point where major manufacturers are considering making them as part of their product line.

2010

At the dawn of this decade there is a new direction for the existing and new cyclotrons precipitated by the reactor shutdowns that created a Tc-99m shortage. A number of proposals have been put forward to demonstrate that clinical needs for the SPECT agent, Tc-99m, can be met by using accelerators to produce Mo-99 and/or Tc-99m. The cyclotron approach making use of the 100Mo(p,2n)99mTc reaction has been driven by funding from the Canadian government to two separate collaborations [22]. While a detailed discussion on this topic is beyond the scope of this article, preliminary results indicate that existing cyclotrons installed in centers designed for PET can be used to supply sufficient Tc-99m to meet the needs of the local community. In addition the dosimetry produced from using cyclotron Tc-99m was essentially the same as from generator produced Tc-99m (on the order of 1% increase). The economic model appears favorable as well.

With the advances in genomic research and improved imaging techniques there is a growing interest in what is being called personalized medicine whereby the diagnostic approach to a patient will be based on their particular expression of disease. The monitoring of the efficacy of treatment will also follows the lines of using functional imaging at the early stages of therapy so that alterations to treatment can provide the highest probability of success.
In order to pursue this approach cyclotron companies are exploring the concept of unit dose production of tracers based on F-18 and C-11. The approach for C-11 recognizes that there will be a need to produce small quantities multiple times throughout the day. The cyclotrons would have to be integrated with automated chemistry systems that provide a seamless product, cyclotron, chemistry and quality assurance. Since the amount of tracer would be greatly reduced, the cyclotrons envisioned for this approach would be of low energy and modest beam currents, <8MeV and <50 μA, respectively. Their operation would be totally automatic and requiring minimal maintenance or intervention.

Conclusions
As with all technological developments the advances in cyclotron design are driven by advances in other disciplines, either as a push or pull. The push comes from, for example, better electronics while the pull comes by way of the needs of the user community, as with higher production yields for 18F-FDG distribution.

One of these technological advances that keeps the interest of the cyclotron designer is the idea to build a truly miniature cyclotron based on superconducting technology. Such designs indicate that the modern cyclotron of approximately 8 MeV could resemble Lawrence’s first cyclotron, almost fitting into your hand. The difficulties are the required shielding and the sophisticated cryogenic system needed. The targets will generate the same gamma and neutron fields regardless of the physical size of the cyclotron. Thus the advantage of the miniature cyclotron is soon lost with multiple tons of shielding.

Overcoming these concerns represents the challenges for the next few years; we may yet have a table-top espresso cyclotron.

References
Predictive Capabilities of Nuclear Theories

The scientific method uses experimentation to assess theoretical predictions. Based on experimental data, the theory is modified and can be used to guide future measurements. The process is then repeated, until the theory is able to explain observations. The positive feedback in the loop “experiment–theory–experiment–” can be enhanced if statistical methods are applied to determine the independence of model parameters, parameter uncertainties, and the errors of calculated observables.

Nuclei communicate with us through a great variety of observables. Some are easy to measure; some take considerable effort and experimental ingenuity. But not every observable has a potential to impact theoretical developments: some are more important than the others. Nuclear theory is developing tools to deliver uncertainty quantification and error analysis for theoretical studies as well as for the assessment of new experimental data. Statistical tools can also be used to assess the information content of an observable with respect to current theoretical models, and evaluate the degree of correlation between different observables. Such technologies are essential for providing predictive capability, estimate uncertainties, and to assess model-based extrapolations— as theoretical models are often applied to entirely new nuclear systems and conditions that are not accessible to experimentation.

The need for uncertainty estimates in papers involving theoretical calculations of physical quantities has been long recognized in the atomic community. The current situation has been well described by an Editorial in Phys. Rev. A 83, 040001 (2011):

It is all too often the case that the numerical results are presented without uncertainty estimates. Authors sometimes say that it is difficult to arrive at error estimates. Should this be considered an adequate reason for omitting them? … There is a broad class of papers where estimates of theoretical uncertainties can and should be made. Papers presenting the results of theoretical calculations are expected to include uncertainty estimates for the calculations whenever practicable, and especially under the following circumstances: (1) If the authors claim high accuracy, or improvements on the accuracy of previous work; (2) If the primary motivation for the paper is to make comparisons with present or future high precision experimental measurements. (3) If the primary motivation is to provide interpolations or extrapolations of known experimental measurements.

A one-day workshop, held at the Institute of Nuclear Physics in Krakow (Poland), 25 August 2012, was devoted to a question on how to improve and optimize the mutual interaction between experiment and theory (Figure 1). Some of the compelling questions discussed were:

1. How to estimate statistical and systematic errors on calculated quantities?
2. How to assess the uniqueness and usefulness of an observable (i.e., its information content with respect to current theoretical models)?
3. How to validate and verify model-based extrapolations?
4. What experimental data are crucial for better constraining current nuclear models?
5. How can statistical tools of nuclear theory help planning future experiments and experimental programs?

There were no formal talks; most of the time was devoted to discussion. Based on the exchanges during the meeting, it is clear that the progress in quantification of theoretical uncertainties is badly needed, especially when planning the new experiments and experimental programs. In this context, excellent opportunities are offered by the high-performance computing. It has been decided to hold more such meetings in the future, to assess and stimulate the developments in this area of nuclear theory, and to increase community awareness of new opportunities.

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Figure 1. Workshop participants.

The eleventh edition of the International Conference on Hypernuclear and Strange Particle Physics took place on 1–5 October 2012 in Barcelona, Spain. The objective of this triennial conference series is to advance in the understanding of phenomena related with the presence of strangeness in a nuclear environment. The present edition attracted over 150 scientists of 20 different countries, who had the opportunity of hearing the latest research progress on the field by means of 37 plenary talks, 56 oral contributions in parallel sessions, and about 50 poster displays.

The conference began with a session dedicated to the memory of Osamu Hashimoto and Slavek Sotona, who passed away prematurely a few months prior to the event. Satoshi Nakamura and Petr Bydzovsky provided an overview of the latest experimental and theoretical advances in the electromagnetic production of hyperons and hypernuclei, while also revising the achievements that their scientific mentors had made in this field, a tribute that also helped the younger participants to appreciate better the legacy they inherit.

The present status and recent developments on the structure of hypernuclei were widely reported, such as the sub-MeV energy resolution results from (e,e'K+) reactions at Jefferson Lab or a new γ transition in $^{12}_ΛC$ from a KEK γ-ray spectroscopy experiment, posing a challenge to shell-model calculations that may need to incorporate the effects of a three-body ΛNN term. Particularly interesting was the report on the very neutron-rich hypernucleus $^6_ΛH$, observed for the first time by the FNUDA collaboration. Combined with accurate ab-initio calculations, light hypernuclei measurements provide an opportunity to establish the properties of the bare hyperon–nucleon interaction, including its fine details, such as possible charge symmetry breaking effects or three-body forces. The feasibility of precise hypernuclear spectroscopy from weak pion decay, proposed for Jefferson Lab and already initiated at the Mainz Microtron MAMI, was also highlighted.

There has been a considerable progress in the theoretical description of baryon–baryon interactions in the strange sector. The available scattering data is now very well described with interactions obtained from chiral effective field theory up to next-to-leading order in the chiral counting. Lattice QCD methods, which simulate strongly interacting systems in a discrete space–time in terms of quark–gluon dynamics, may obtain appropriate baryon–baryon interactions and the binding energies of few-body bound hypernuclear systems in a not too distant future. At present, the volume and pion mass extrapolations required in lattice models benefit from the link to chiral effective theories that obey the relevant symmetries of QCD. An example is the lattice bound ΛΛ dibaryon, which was shown to evolve toward a ΛΛ resonance after performing a chiral extrapolation to the physical pion mass employing the proper ΛΛ, ΞN, and ΣΣ thresholds.

The recent discovery of the millisecond pulsar PSR J1614-2230 with a mass of $1.97 ± 0.04 M⊙$ poses a challenge to ab-initio theoretical models.
that unavoidably predict the appearance of hyperons in neutron stars, softening the equation-of-state and producing maximum masses below $1.5 \, M\odot$. Possible solutions to this “hyperonic puzzle” were discussed, such as a transition to quark matter before hyperons appear, an increase of the vector repulsion among hyperons, or the effect of hyperonic three-body forces. Heavy-ion collisions also offer an opportunity to study extreme forms of matter. Specially promising was the measurement of $\Lambda\Lambda$ correlations as a tool to discriminate between theoretical interaction models.

A few talks were devoted to revise the developments on antikaon dynamics in nuclei, a key issue in the search for bound kaonic nuclear systems. The properties of the $K\Lambda$ interaction are intimately connected to those of the nearby $\Lambda(1405)$ resonance and the most recent experimental efforts for extracting them from electromagnetic reactions at Jefferson Lab or from proton–proton reactions at HADES were amply debated. The more precise values of the energy-shift and width of kaonic hydrogen obtained by the SIDDHARTA collaboration have contributed to better constraining the theoretical models. However, the extrapolation toward nuclear systems is not unambiguous. Chiral-motivated interactions produce moderate attractive antikaon optical potentials but good fits to kaonic atom data are also obtained with deeper ones. What is certain is that, in all cases, the widths obtained for $K^+p\Lambda$ and other few-body kaonic systems are larger than their binding energies, making these states very difficult to be identified in ongoing experimental searches.

Hypernuclei decay in about $10^{-10}$ s through weak interaction processes. While the two-body $\Lambda N \rightarrow NN$ mechanism is the dominant decay mode, the branching ratio of the three-nucleon $\Lambda NN \rightarrow NNN$ channel has been established to be about 20% by the FI-NUDA collaboration, with improved precision over the earlier KEK result. Studying the weak decay of $s$-shell $^4\Lambda\Lambda H$ and $^4\Lambda\Lambda He$ hypernuclei will help in understanding details of the decay mechanism, such as whether the $\Delta I = 1/2$ rule observed in hadron weak decays is also valid for the two-baryon reaction.

A few aspects of the physics of heavier flavor systems, which can bring a broader perspective to the nuclear phenomena associated to strangeness, were also discussed. Some of the newly discovered quarkonium-like particles are conjectured to be either bound two-meson systems or tetraquark states. A sharp resonance below the $\Lambda_c(2595)N$ threshold in the DNN system has been predicted. This is connected to the molecular $DN$ character of the $\Lambda_c(2595)$, which is similar to what has been already seen in the lighter sector, examples being the negative parity $\Lambda(1405)$ resonance, widely accepted as a $K-N$ quasi-bound state, or some positive parity $\Lambda$ and $\Sigma$ states that have been reported to be possibly identified with molecular systems of two mesons and a baryon.

The community is now looking forward to the future results of $(e,e'\gamma)$ reactions from the Jefferson Lab 12 GeV upgrade and from MAMI, and especially to those from the J-PARC facility, where experiments on practically all aspects in strangeness nuclear physics will be conducted. Many new and exciting physics are certainly going to be available for the next edition of this conference that will be held in Sendai (Japan) in 2016.

![Figure 2. An exhibition of traditional Catalan castell (human castles).](image)

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Running over a week in August 2012, the XII International Symposium on Nuclei in the Cosmos (NIC XII, http://www.nic2012.org) brought 250 international researchers to Cairns (Australia) to present their findings on topics at the interface between nuclear physics and astrophysics (Figure 1). Nuclei in the Cosmos (NIC) is the premier conference series in Nuclear Astrophysics, the multidisciplinary research field that addresses key scientific questions of our century like the origin of the elements, the physics of thermonuclear stellar explosions, and the nature of dense nuclear matter. The conference is held every two years since 1992 in different locations, from Europe, where it started, to the United States, Japan, and last year for the first time in Australia. Each of the conferences in the series raises a phenomenal amount of interest due to the fact that they are truly interdisciplinary, bringing together researchers in the fields of astronomy and astrophysics, nuclear physics, as well as meteoritics and planetary science. The tradition of this series of conferences is to keep each of those different research communities updated on developments in the other related topics and facilitate close collaborations. It is common that NIC conferences foster the start-up of new collaborative projects. As traditional, NIC XII was preceded by a “NIC school” sponsored by and held at the Australian National University (ANU) in Canberra the week before the conference. The NIC school is aimed at preparing students and early-career postdocs in the topics presented at the NIC conference.

For NIC XII, we had almost three hundred abstract submissions to be considered for less than fifty oral contribution slots available. To give more people the chance to present their work on the stage, we added into the program more than 100 one-minute poster presentations. Selected highlights of the program included talks by a number of high-profile peers: Nobel Laureate Brian Schmidt (ANU), who talked about SkyMapper, the new telescope that will map the southern sky; Adam Burrows (Princeton), who reviewed the state of the field of core-collapse supernovae; Gianluca Imbriani (Naples), who presented the most important results coming from the only underground laboratory in the world dedicated to the measurements of nuclear reaction rates, the LUNA (Laboratory for Underground Nuclear Astrophysics) laboratory at the Na-
tional Laboratory of Gran Sasso in Italy; Almudena Arcones (Darmstadt), who discussed the origin of half of the elements heavier than iron via rapid neutron captures, a challenging problem from both the astrophysics and nuclear physics perspectives; and Alison Laird (York), who reviewed the large progress made in the last twenty years on direct measurements of key nuclear reactions at or near stellar energies due to the availability of radioactive ion beams and low background facilities. The conference program also benefited from researchers and topics that may not have been considered previously in connection to Nuclear Astrophysics but have the high potential to connect with the field. For example, Luciano Rezzolla (MPG) talked on modeling the merging of binary neutron stars and presented results computed including general relativity, Max Pettini (Cambridge) showed observations of elemental abundances in near-pristine gas at high redshifts, and Jirina Stone (Tennessee and Oxford) discussed the possibility of constraining the high-density nuclear equation of state using low-density, high-temperature matter, such as is created in heavy ion collisions in the laboratory by experimental nuclear physicists. The conference proceedings are available via open online access by Proceedings of Science at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=146

Feedback from the attendees was collected via invitation to participate in an online survey, which was filled out by roughly half of the participants. Overall the conference program was rated very well, with over 80% rating the program content, standard, and relevance as excellent or very good. A couple of specific comments are reported here as examples: “It was a very stimulating and engaging conference. I enjoyed it very much and learnt a great deal” and “It was an excellent meeting, valuable for all the attendees.” A common comment has been that the program was well balanced. Most people also highlighted that they liked the idea of the one-minute poster presentations.

NICXII was sponsored by the Monash Centre for Astrophysics (MoCA), the (ANU) Research School of Astronomy and Astrophysics (RSAA) of the Australian National University, the Ian Potter Foundation, the International Union for Pure and Applied Physics (IUPAP), the Australian Astronomical Observatory (AAO), the Research Centre for Astronomy, Astrophysics, and Astrophotonics of Macquarie University, the Research Centre for the Subatomic Structure of Matter of The University of Adelaide, the Centre for Astrophysics and Supercomputing of Swinburne University of Technology, and Tyrrells’ wines, who provided delicious wines for the social functions.

The next appointment with Nuclei in the Cosmos is in July 2014 in Debrecen, Hungary.

MARIA LUGARO
Chair of the NICXII Organising Committee, Monash Centre for Astrophysics (MoCA)

REMEMINDER

Check the calendar section of NPN for upcoming events of interest to the nuclear physics community.

If you are planning a future event, send the pertinent information to Gabriele-Elisabeth Körner (sissy.koerner@ph.tum.de) as soon as possible.
In Memoriam: Paul Kienle (1931–2013)

On 29 January 2013, Paul Kienle, Professor Emeritus at the Technical University of Munich, passed away at the age of 81 years in his beloved city where he had lived, studied, taught, mentored, and researched for altogether six decades. As many will remember, Paul Kienle was one of the founding fathers of NuPECC and thus of this journal, Nuclear Physics News. He would have smiled, in his knowing way, at the thought of a 2-page obituary on these pages on his behalf.

Paul Kienle entered the TU Munich in 1949 to study “Technical Physics.” In his diploma and Ph.D. theses he investigated discharges of Geiger-Müller counters and developed the first position-sensitive counters for the survey of radiation fields. He always thought of these studies as the seeds for his method-driven approach to physics.

After his dissertation in 1957, Paul Kienle was one of the first scientists in an exchange program with Brookhaven National Laboratory, where he spent one year learning about radiation safety at research reactors and accelerators. This he then applied, after his return, to the Munich research reactor as the responsible radiation officer.

Already at Brookhaven he had developed his interest in nuclear spectroscopy, which he pursued at Munich through decay spectroscopy of fission products. From 1969 on he worked on the effect newly discovered by his long-time classmate and friend at the TUM, Mössbauer. Here Paul Kienle focused on the discovery of new Mössbauer transitions, their nuclear parameters, as well as on internal fields and electron densities in solids.

In 1963 he accepted a professorship for nuclear physics at the Technical University of Darmstadt where he built a strong program in Mössbauer spectroscopy. In 1965 he returned to the TU Munich. His research in this period covered a broad spectrum; from new nuclear moments, shrinking of nuclei in rotational excitation due to the Coriolis effect on pairing, to very sensitive time-reversal experiments, for example.

Paul Kienle was also strongly involved in developing the structure of the new Physik-Department at the TUM, and in establishing together with the Ludwig-Maximilian University of Munich the joint Tandem-Accelerator Laboratory at Garching. This was the beginning of Paul Kienle’s research activities in heavy-ion physics.

Together with the 1976 commissioned UNILAC at GSI, his group pursued a broad program with lighter beams at Munich and uranium beams at GSI: From transfer reactions to discrete states, to transport phenomena in deep-inelastic multi-nucleon transfers, to δ-ray and positron emission in supercritical fields in uranium–uranium collisions.

The breadth of his group’s work is also illustrated by the successful realization of a heavy-ion pumped laser, and spin-dependent photo absorption of circularly polarized X-rays, now a well-established method in magnetic research at synchrotron radiation facilities.

In 1984 Paul Kienle took on the directorship at GSI. Under his guidance the new concept of heavy-ion synchrotron plus high-energy ion storage ring was developed, proposed, approved (1985) and completed (1990) in record time. The SIS-ESR facility allowed a broad research program; from fundamental research to applications such as heavy-ion cancer therapy.

Paul Kienle’s personal interests focused on the successful electron-cooling of highly stripped ions; with the demonstration of an ordered linear ion chain; bound-beta decay; and electron capture decays of highly stripped ions involving mono-energetic neutrinos, as examples.

In strong-interaction physics, Paul Kienle’s interest focused on exotic nuclei such as the discovery of doubly magic $^{100}$Sn, on anti-proton production, and on deeply bound pionic states in heavy nuclei and their relevance for the order parameter in spontaneous chiral symmetry breaking in a nucleus, and most recently on deeply bound kaonic states. Much of the latest work was as emeritus, heading the Stefan-Meyer Institut in Vienna. In the context of the future facilities at GSI, Paul Kienle proposed the high-energy cooler/storage ring for anti-proton physics.

The breadth of Paul Kienle’s scientific work and of his original and substantial contributions to each of the research areas involved is impressive. His scientific leadership is internationally highly recognized. His input, advice, and guidance has been sought in
In Memoriam: David Bodansky (1924–2012)

The Department of Physics at the University of Washington lost a valued and valuable colleague on 2 December 2012. Born in March of 1924, David Bodansky graduated and received advanced degrees from Harvard in the 1940s. He was at Columbia University as an instructor and then associate from 1950–1954 and joined the Department of Physics at the University of Washington in 1954. He was chair of the Department from 1976–1984. He retired from teaching in 1993, but remained active in Physics.

David was an AEC Predoctoral fellow, and received two Sloan fellowships, which he spent at the Niels Bohr Institute in Copenhagen between 1959–1963. He also received a Guggenheim fellowship in 1966 and spent it at the California Institute of Technology and a later one in Copenhagen. He served on POPA from 1985–1987 and was its chair in 1995.

In his early years, David was active in nuclear physics, intermediate energy physics, and experimental astrophysics. He was one of the first to test time reversal invariance in the strong interactions.


David is survived by his wife and two sons.

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2013

**July 1–3**
Krakow, Poland. EURISOL Topical Meeting 2013 “Going to the limits of mass, spin and isospin with heavy Radioactive Ion Beams”
http://eurisol.ifj.edu.pl/

**July 1–19**
Seattle, WA, USA. TAENT/INT course on “Nuclear forces and their impact on structure, reactions and astrophysics”
http://www.int.washington.edu/PROGRAMS/taent13/

**July 8–12**
ECT* Trento, Italy. Nuclear Structure and Astrophysical Applications
http://www.ectstar.eu/

**July 14–19**
Chiba, Japan. 12th Asia Pacific Physics Conference (APPC12)
http://www.jps.or.jp/APPC12/index.html

**July 22–26**
East Lansing, MI, USA. Third International Symposium on Nuclear Symmetry Energy (NuSYM13)
http://www.nucl.phys.tohoku.ac.jp/nusym13/index.html

**August 5–8**
Bruges, Belgium. 11th International Topical Meeting on Nuclear Applications of Accelerators Acc App 2013
http://www.accapp13.org/

**August 19–22**
College Station, TX, USA. International Workshop on Nuclear Dynamics and Thermodynamics
http://wwwndt.tamu.edu/

**August 23–24**
East Lansing, MI, USA. Low-Energy Community Meeting
http://meetings.nscl.msu.edu/CommunityMeeting2013/

**August 25–31**
New York, USA. 35th International Free-Electron Laser Conference FEL2013
http://www.c-ad.bnl.gov/fel2013/

**September 1–7**
Piaski, Poland. XXXIII Mazurian Lakes Conference on Physics
http://mazurian.fuw.edu.pl/

**September 9–13**
Villigen, Switzerland. 3rd International workshop on the Physics of fundamental Symmetries and Interactions at low energies and the precision frontier - PSI 2013
http://www.psi.ch/psi2013/

**September 16–20**
Vancouver, Canada. 20th International Conference on Cyclotrons and their Applications (CYCLOTRONS'13)
http://cycl13.triumf.ca/

**September 16–24**
Erice, Italy. Neutrino Physics: Present and Future

**September 19–21**
Takayama, Japan. 8th Workshop on the Chemistry of the Heaviest Elements (CHE 8)
http://asrc.jaea.go.jp/CHE8/

**September 22–27**
Kanazawa, Japan. Asia-Pacific Symposium on Radiochemistry (APSORC-13)
http://www.radiochem.org/apsorc13/

**September 23–27**
Casta-Papiernicka (Bratislava), Slovakia. 1STROS2013
http://istros.sav.sk/

**September 23–27**
Paris, France. 16th International Conference on RF Superconductivity SRF 2013
http://www.srf2013.fr/

**September 23–November 15**
INT Seattle, USA. Quantitative Large Amplitude Shape Dynamics: Fission and Heavy Ion Fusion

**September 30–October 4**
Roma, Italy. 13th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon (MENU 2013)
http://menu2013.roma2.infn.it/

**October 6–11**
San Francisco, CA, USA. 14th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 2013)
http://icalepcs2013.org/

**October 7–11**
Sao Sebastiao, SP, Brazil. Fourth International Workshop on Compound-Nuclear Reactions and Related Topics (CNR*13)
http://www.ita.br/CNR2013/

**October 8–12**
Moscow, Russia. 63d International Conference on Nuclear Physics “Nucleus2013”

**October 13–17**
Berkeley, CA, USA. 11th International Conference on the Health Effects of Incorporated Radionuclides (HEIR 2013)

**November 13–15**
Bern, Switzerland. 2nd Int. Workshop on Antimatter and Gravity (WAG 2013)
http://www.einstein.unibe.ch/workshops/wag2013.html

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