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Cover Illustration: The Q3D Spectrograph at the Munich Tandem Accelerator Laboratory – see article on page 5.
Status and Development for Nuclear Science in China

Nuclear physics is one of the important fundamental subjects in China and is developing in the most interesting fields from the basic to application, low energy to higher energy, w/o accelerator based, to domestic research and international collaboration. With the economic burst and clean energy demand, the Chinese government is investing more funding for mega-scale facilities for nuclear science research as well as its advanced nuclear energy systems and education.

Currently, the main research teams come from the Chinese Academy Sciences (CAS) and more than 10 universities. The domestic research facilities are distributed over a number of research institutes, for example, Institute of Modern Physics (IMP, CAS), Institute of High Energy (IHEP, CAS), China Institution of Atomic Energy (CIAE), and Shanghai Institute of Applied Physics (SINAP, CAS).

IMP operates the Heavy Ion Research Facility in Lanzhou (HIRFL) to provide the full ions in the energy from low energy to 1 GeV/A ranges. It consists of the Sector Focusing Cyclotron, the Separated Sector Cyclotron, the main and experimental Cooler Storage Rings (CSRm and CSRe), and so on. Through 60 years of development, HIRFL has become a leading research platform of heavy-ion science in China, collaborating with over forty institutions worldwide. The major research fields at IMP cover ion accelerator physics and technologies, heavy-ion physics, and heavy-ion applications. Recently, some interesting results on the precise mass measurement of proton-rich nuclei and research on the structure of exotic nuclei have been obtained as well as several heavier isotopes being synthesized. Some advanced technology on heavy ion accelerator, ECR ion source, and intensity SCL has been achieved. There are some important disciplines and applications (e.g., heavy ion cancer therapy, accelerator driven fission energy).

IHEP is one of nuclear science institute in CAS and its main researches include the hadron and particle physics. Based on the Beijing Electron-Position Collider (BEPC), a large number of J/ψ data provides the great chance for hadron physics experiments, such as exotic particle Zc(3900) measurement. Other well-known experiments are the neutrino θ13 precise measurement in the Daya-Bay 6 sets 3GWt reactor and some cosmic ray observation. In the electron accelerator and detector field, IHEP is in the leading position in China. Besides the BEPC, the synchrotron light source and spallation neutron source were designed and constructed in last 30 years. Another mega-scale neutrino experiment based on reactor neutrino, JUNO, is under construction and is planned to take data in 2020.

CIAE is the first Chinese nuclear research institute, beginning in the 1950s, and some institutes originate from it, such as IMP and IHEP. Now, besides nuclear energy research, CIAE still keeps a team to study heavy ion physics, nuclear astrophysics, nuclear theory, measurement of nuclear data, and so on. The Beijing Rare Ion Beam Facility is being commissioned; it is based on a 100 MeV compact proton cyclotron and 15MV tandem post accelerator ISOL type RIB facility and some upgrade activities to increase RIB beam energy are coming. Additionally, CIAE leads an underground nuclear astrophysics experiment (JUNA) in the China Jinping Underground Lab, which includes a 400 KV platform accelerator and a couple of gamma, neutron, and charged particle detectors planned to start operation in 2020.

SINAP main research activities are on synchrotron light sources and nuclear energy recently. However, there remains a very active group focusing on studies of radioactive beam physics and relativistic heavy ion collisions based on big facilities outside as well as nuclear theory. They lead Chinese groups in collaboration with the RHIC-STAR detector at BNL, USA and played the leading role in a series of discovery of antimatter nuclei and the measurement of antiproton interaction with the STAR BNL group and others.

Currently, there are some ongoing mega-scale nuclear research facilities, which are world class and more open for international collaboration.

IMP is collaborating with many institutes and universities to establish a new research center with a High Intensity Heavy-ion Accelerator Facility (HIAF) and Chinese Initial Accelerator Driven System (CIADS) at a new site of Huizhou, Guangdong Province starting this year. Based on the intense ion beam of HIAF + CIADS, its main researches are: nuclear structure and astrophysics, hadron physics, a few topics of foundation physics such as electron pair production in vacuum under ultra-high field, high energy-density matter physics, and accelerator...
driven for close fuel cycle. The HIAF is designed to accelerate full ions in 1 GeV/A for U and 10 GeV for proton, the high \(^{238}\)U beam intensity \(\sim 100\) kJ/ppp for producing RIB. CIADS is designed to accelerate proton energy to 500 MeV with >2.5 MW CW beam power, spallation target, and 10 MW total power including blanket. It will be the most powerful ISOL-type RIB by integral of 10 MW CIADS + HIAF in the next 10 years.

Besides for heavy ion physics programs, the photon facility is also very useful for exploring nuclear structure and nuclear astrophysics at MeV photon energy as well as the hadron structure at GeV photon energy. One beam-line, called the Shanghai Laser-Electron Gamma (SLEGS) source, is under construction based on the SSRF upgrade program at SINAP. A 0.5–20 MeV photon beam will be delivered by the electron-laser Compton back-scattering technique and is expected to be open for public users in 2021. Very recently, a mega-scale facility named the Shanghai Coherent Light Facility (SCLF), an advanced and bright hard X-ray FEL, will be constructed near the SINAP-SSRF campus. A high quality 8-GeV electron beam will be used to produce coherent hard X-ray FEL. It also provides an opportunity to produce high energy photon beams (e.g., a 3 GeV photon beam could be produced by using the external laser scatters with an 8 GeV electron, and an almost 8 GeV photon could be obtained by using the 8 GeV electron scatters with the SCLF x-ray photons).

Besides the ongoing projects, there are some proposals for the next five-year national plan, such as the Beijing Isotope-Separation-On-Line neutron-rich beam facility (BISOL).

Activities of the Chinese nuclear physics community are not only focused on domestic nuclear physics facilities; they also participate in large-scale international collaboration. For example, six Chinese institutions have participated in the RHIC-STAR collaboration since 2001. The Chinese team has made a great contribution on the multi-gap resistive plate chamber (MRPC) based barrel Time-of-Flight detector, Muon Telescope Detector, and High Level Trigger system, and is now collaborating for the inner Time Project Chamber, the endcap TOF, and the Event Plane Detector detectors for the STAR detector complex. LHC-ALICE collaboration in China is contributing to Inner Tracker System and Muon Forward Tracker upgrades. The JLab Chinese group is contributing to the SOLID detector upgrade, and the FAIR-CBM China team is contributing to the MRPC-based TOF system.

Additionally, a China–U.S. Theory Institute for Physics with Exotic Nuclei (CUSTIPEN) was officially launched on 1 May 2013 with the support of U.S. DOE and NSFC grants.

Concerning nuclear application, nuclear fission energy and hadron cancer therapy are the most active fields in China. Besides the CIADS project, a thorium molten salt reactor (TMSR) is under R&D, mainly by SINAP with the support of the Chinese Academy of Sciences strategic pilot project. There are two sets of heavy ion cancer therapy clinic facilities in a hospital that will get a license soon, and some proton therapy facilities are being constructed that are supported by local government and some companies.

Wenlong Zhan
Chinese Academy of Science
Physics at the Munich Tandem Accelerator Laboratory

The Tandem accelerator situated in Garching, just 20 km north of Munich, is of the “Emperor” (MP) series manufactured by High Voltage Engineering Corporation (HVEC). It delivered the first beams for experiments in 1970 and came close to its design voltage of 10 MV. In 1991 the tubes were exchanged to the extended version of HVEC. Routine operation at a terminal voltage of 14 MV was then possible.

As negative ion sources we use single-cathode sputter sources for most ions and a commercial multicusp ion source for intense hydrogen-beams. Polarized hydrogen-beams are available as well. A pulsed beam with 2 ns width can be produced by means of a chopper and a buncher on the low energy side and a chopper behind the tandem.

In 2002 the Maier-Leibnitz Laboratory (MLL) was founded by the Ludwig-Maximilians Universität and the Technische Universität München, which now operates the accelerator lab as one of its research activities besides high-energy, neutron, laser, and medical physics. In a “laboratory portrait” (Nuclear Physics News 2001) a report on the lab was given with a special emphasis on interdisciplinary research. Here we also want to emphasize the important role that our Q3D spectrograph played in the last decade in nuclear structure physics and its impetus on neighboring fundamental disciplines, as astro- and particle physics.

The Q3D Magnetic Spectrograph

Today, the Q3D magnetic spectrograph at the MLL is unique in the world as a precision instrument for nuclear structure physics. It was designed as a double-focusing instrument by Harald Enge (MIT) around 1970 after he had designed the split-pole spectrograph and several others. The first two Q3Ds were built identically for Heidelberg and Munich (Figure 1). They were the first intended for detectors with electronic readout and therefore had a huge dispersion of $\delta x/(\delta p/p) \approx 20$ cm%/along the focal plane, which is actually bent and tilted by about 45° against the incoming particles. The bending radius is 0.95–1.05 m and the maximum field about 1.6 T. The accepted solid angle is 14 msr, with a horizontal angle of 6.8°. For the correction of the kinematic walk over this angular range a magnetic multiple element was provided between the 1st and 2nd dipole, where there is an intermediate vertical focus. In total an energy resolution of $2 \times 10^{-4}$ (FWHM) can be achieved over an energy bin of 15%. Angular distributions can be measured between 0° and about 140°. As detectors for light particles (p,d,t,3He,$\alpha$) in the focal plane we use most often a 0.9 m long detector, based on two single-wire proportional counters, one with a readout of 3.5 mm wide cathode strips for position ($\delta x \sim 0.1$ mm) and energy-loss information and a scintillator for the residual energy. For heavy ions we have two detectors: both use proportional counters for position and energy loss; one measures the residual energy in an ionization chamber, the other one in 128 Si-detectors covering 1.0 and 1.4 m of the focal plane, respectively.

Nuclear Structure Studies

The Heaviest Doubly Magic Nucleus $^{208}$Pb

Excited states in $^{208}$Pb have been studied extensively at the Q3D in the last decade. All the information gathered so far has been summarized in a detailed paper [1]. Besides $^{208}$Pb(d,d') and $^{206,207,208}$Pb(d,p) reactions a special type of $^{208}$Pb(p,p') reaction has been used, where the energy of the projectile is chosen such that it populates states in $^{209}$Bi that are isobaric analog states (IAS) of $^{209}$Pb states. The outgoing proton then leaves the final nucleus in particle-hole states, where the particle is determined by the IAS (i.e., this type of reaction is equivalent to a neutron pickup from a single particle state in $^{209}$Pb). Thus, neutron particle-hole states have been populated with the particle in the orbitals $g_{9/2}$, $i_{11/2}$, $j_{15/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$. These resonances are reached with proton energies between 14.9 and 17.5 MeV and have widths between 0.2 and 0.3 MeV. It is claimed that all states up to 6.2 MeV of excitation, 150 in total, have been firmly identified and characterized with spin and parity.

Fission of Hyperdeformed States in Actinide Nuclei

The study of the multiple-humped potential energy landscape in actinide nuclei led to the establishment of the existence of a hyperdeformed (axis ratio 3:1) deep third minimum in $^{236}$U. Employing (d,p) reactions in coincidence with fission such hyperdeformed bands were found as well in $^{232}$U and also in the odd-odd nuclei $^{232}$Pa and $^{238}$Np ([2] and refs. therein; see Figure 2). Absolutely essential for these identifications was the excellent...
resolution of about 6 keV for the detected protons. Based on the observed level densities the excitation energy of the third potential minimum could be extracted.

Clustering in Light Nuclei

Clustering of α-particles plays an important role in light nuclei. The prime example is the 1st excited 0+ state in 12C that was postulated by F. Hoyle 60 years ago close to the α-emission threshold and thus responsible for the He burning in stars and the production of carbon. This state is believed to be well represented by an almost linear chain of three α-particles. Clusters consisting of α-particles and neutrons exist as well. For example, 18O could have a structure of 16C+α+2n. Using the (6Li,p) reaction on 12C, 13C, and 14C I targets we studied states in 18O, 19O, and 20O, where an α-particle and two neutrons are added to the target nucleus. Even far above the particle emission thresholds narrow states exist. Many states were observed for the first time and some can be grouped into rotational bands. α-transfer with the (6Li,d) reaction was used to study states in 13C and 16O. Here we used, in coincidence with deuterons, detected in the focal plane detector of the Q3D, break-up particles of the residual nuclei to measure absolute values of the partial decay widths. The break-up particles were detected in large area, position sensitive Si detectors. Thus, the different break-up channels and even the states in the nucleus, breaking up, can be distinguished. From this information and the particle decay widths some of the observed states can be characterized with respect to their underlying molecular structure. Using the 9Be(3He,t) reaction excited states in 9B have been studied recently [3], which all decay into p+α+α. With sophisticated conditions on the break-up particles the energy and width of the first excited state could be determined, indicating a shell-model structure rather than a cluster structure.

Nuclear Astrophysics

Nova explosions occur when a white dwarf in a binary system has accreted hydrogen from its companion star until a thermonuclear runaway has been triggered with subsequent ejection of material. Thus light elements are formed and dispersed into the interstellar medium. Since the relevant nuclides lie close to the valley of stability, the quantities necessary to calculate the reaction rates as a function of temperature are accessible to high resolution experiments. The calculated element formation can then be compared with the results of infrared and radio observations.

We investigated levels close to the proton emission threshold in nuclei that are formed in the reaction pathway of Novae. Nuclear states in 19Ne, 20Na, 24Al, 28P, 32Cl, 36K, 27Si, 31S, and 34Cl as well as 35Cl [4] and 35Ar [5] have been excited with 3He and d induced reactions. Precise excitation energies and spin-parity assignments could be obtained even for not resolved states by measuring angular distributions.

One of the main neutron sources for the s-process is the 13C(α,n)16O reaction. Thus, states in 17O close to the α-threshold influence the n-production. And states above the n-threshold may act as neutron-poison through the 16O(n,γ)17O reaction. We have used the 19F(α,d)17O reaction to measure the excitation spectrum of 17O between 3.8 and 7.8 MeV (Figure 3) and could determine position and total width of the relevant levels with much better precision than before [6], especially for the 1/2− state just above the α-threshold with Eγ = 6363.4(3.1) keV, Γ = 136(5) keV. Also states in 21Ne in the Gamow-window, which again can act as a neutron-poison, have been investigated using the 20Ne(d,p)21Ne reaction [10].

Nuclear Structure for the CKM Matrix

The eigenstates of the quarks in weak interaction are connected to the mass eigenstates by a unitary transformation through the CKM matrix. The most precise determination of the first element of that matrix comes from nuclear beta-transitions between IAS with spin 0, where Gamow-Teller transitions are forbidden. Besides the main ingredients, partial half-life and decay energy, detailed nuclear structure information is also necessary for the small but important corrections. Before the powerful Penning traps
came online, precise measurements of reaction Q-values provided the decay energy. A number of values where determined with ($^3$He,t) reactions at the Munich Q3D in the 1970s. But it turned out that they were not compatible with later Penning trap values. To test the accuracy of the reaction Q-values, we determined it for the $^{46}$V decay to $^{46}$Ti. We achieved an uncertainty of 0.27 keV, more precise than the Penning-trap measurements at that time. But the trap magicians [7] promptly improved their precision to 0.10 keV. The recent measurements are all compatible, whereas the 1977 Munich result is off by more than 3σ.

We also measured the Q-values for the decays of the more exotic emitters with N = Z−2: $^{20}$Na, $^{24}$Al, $^{28}$P, and $^{32}$Cl by ($^3$He,t) reactions [8], where the achievable precision is only about 1 keV but improved the previous precision considerably.

To test the theoretical calculations of the “charge dependent” corrections, which take care of the violation of isospin symmetry, we investigated the $^{64}$Zn(d,pol,t)$^{63}$Zn reaction using polarized deuterons. This is the closest reaction on a stable target to investigate pairing properties in the daughter nucleus of the $^{62}$Ga–$^{64}$Zn decay. For a large number of states in the daughter nucleus the spectroscopic factors could be determined and compared with shell model calculations using the same residual interactions as in the calculations of the charge dependent corrections. Discrepancies can now be used to improve the calculations.

Small branchings of the beta-intensity to excited $0^+$ states have also to be taken into account. With the $^{64}$Zn(p,t) and $^{52}$Cr(p,t) [9] reactions we searched for excited $0^+$ states in $^{62}$Zn and $^{50}$Cr, and found some discrepancies with previous assignments. With the new information the feeding of excited states can be determined using gamma detection.

**Nuclear Structure for Neutrino-Less Double Beta-Decay**

If the process of neutrino-less double-β ($0v2\beta$) decay were to be observed, neutrinos would be established as their own antiparticles (Majorana particles) and progress could be made toward determining an absolute scale for the neutrino-mass eigenstates, provided one can reliably calculate the nuclear transition matrix element. As benchmarks to such calculations experimental quantities are necessary.

We have investigated pairing properties for the $^{100}$Mo–$^{106}$Ru system by studying (p,t) reactions on $^{100,102}$Ru and $^{98,100}$Mo targets [10]. Cross-sections were measured at lab angles 6° and 15° to be sensitive to $L = 0$ transitions leading to $0^+$ states. Whereas the $L = 0$ transfer to and from $^{100}$Ru leads almost exclusively to the ground states, about 20% of the $L = 0$ strength goes to excited $0^+$ states in the $^{100}$Mo case. Apparently, $^{100}$Ru is more on the spherical side, whereas $^{100}$Mo seems to be more easily deformable. This shape change between the two partners of the $0v2\beta$ decay tends to make the calculation of the matrix element complicated.

Other $0v2\beta$ pairs are the $^{150}$Nd–$^{150}$Sm and the $^{136}$Xe–$^{136}$Ba system. For the intermediate nuclei $^{150}$Pm and $^{136}$Cs, there existed only very sparse information, although next to two stable isobars. We studied excited states in $^{150}$Pm via the $^{152}$Sm(d,α) reaction and $^{136}$Cs with the $^{138}$Ba(d,α) reaction [11]. A rich spectrum of the two odd-odd nuclei is observed (e.g., Figure 4).

**Nuclear Structure to Interpret EDM Measurements**

The observation of a permanent electric dipole moment (EDM) of a particle would imply a violation of time reversal (T) and parity symmetry (P). The most stringent upper limit to date has been reported for the $^{199}$Hg atom. But to interpret such limits (or possibly finite values) in terms of T-violating couplings of the quarks or their interaction, a detailed knowledge of the nuclear structure is required. To this end we have started to investigate the E1, E2, and E3 strength in $^{199}$Hg and neighboring nuclei by precision spectroscopy with the Q3D [12]. With the $^{200}$Hg(d,d') reaction the E2 excitation strength of the $2^+_1$ and $4^+_1$ states was measured as well as the E3 strength distribution to a number of $3^+$ states. With the $^{200}$Hg(d,t) pickup reaction we populated states in $^{199}$Hg. We obtained an energy resolution of 7 keV (FWHM) and observed a total of 91 states up to an excitation energy of about 3 MeV, more than half of them were previously not known. From the measured angular distributions we will be able to deduce the transferred angular momentum and the spectroscopic factors for many of these states.

**Nuclear Astrophysics using AMS**

For Accelerator Mass Spectrometry (AMS) measurements we use two set-ups. One has a gas-filled 135° dipole magnet (GAMS) for isobar separation followed by an ionization chamber.

![Figure 4. Spectrum of states in $^{136}$Cs.](image)
measuring position, x- and y-angle, total deposited energy, and five energy-loss signals. In addition, it is preceded by a time of flight (TOF) measurement. The second installation is a TOF measurement followed by an ionization chamber and a Si detector for δE and E_{res} measurements. From the many applications we shall report only two.

Radionuclides from Supernovae in the Solar System

Stars with a mass of more than about eight times the solar mass usually end in a core-collapse supernova explosion (SN). Before and during this explosion new elements, stable and radioactive, are formed by nuclear reactions and a large fraction of their mass is ejected with high velocities into the surrounding space. Most of the new elements are in the mass range until Fe, because there the nuclear binding energies are the largest. If such an explosion happens close to the sun it can be expected that part of the debris might enter the solar system and therefore should leave a signature on the planets and their moons. Already in 1996 we had postulated that 60Fe (measured at MLL: T_{1/2} = 2.62 Ma) is a promising isotope to search for such SN debris: lighter radioisotopes are abundantly produced by cosmic rays on atmospheric or meteoritic target nuclei up to 56Fe and 60Ni, but 60Fe could only be produced from the rare target isotopes 62,64Ni. For nuclei with A > 80 a considerable background from fission is expected.

With our GAMS setup we reach a sensitivity for 60Fe/Fe concentrations below 10^{-16}. Indeed, in 1999 we could report evidence for an increased 60Fe content in samples of a deep-ocean crust from the South Pacific. Five years later we had analyzed well-dated crusts from the Central Pacific in depth intervals of 1–2 mm, corresponding to age intervals of 0.4–0.8 Ma and found a clearly enhanced 60Fe content between 2 and 3 Ma ago. However, a search in sediments, which grow a factor of 1,000 faster, did not show a clear enhancement. Only recently, an Australian group [13] as well as our lab [14] found an 60Fe enhancement in sediments from the Indian Ocean and the Pacific for a time period between 1.5 and 3 Ma ago (Figure 5). This long range indicates that more than one SN have deposited dust in the Solar System. To obtain quantitative information, which is not influenced by atmospheric or oceanic distribution, we also analyzed Lunar samples [15], which were provided by NASA. Due to the impact of micrometeorites the Lunar surface is constantly reworked and deposited material is slowly buried. We measured in most Lunar samples down to a depth of about 10 cm an enhanced (up to a factor of 10) 60Fe concentration. From this we obtained an estimate for the total fluence of 60Fe.

Search for Primordial Heavy Elements

Nuclei heavier than 209Bi have most often no long-lived isobar. Therefore, it is sufficient to determine the atomic mass for a unique identification. However, ordinary mass spectrometry is not very sensitive because of molecular background. We have searched with AMS at our TOF system for long-lived (primordial) isomers of 211–218Th, which had been claimed before by a group around A. Marinov, and could disprove their claim. Another disproval that we could accomplish was for primordial 244Pu, claimed by D. C. Hoffman and her group in 1971 [32]. Since the half-life of 244Pu is 1/56 of the age of the Solar system, their observation was surprising. Our result was a 2σ upper limit for the 244Pu concentration a factor of 6 smaller than the claim by Hoffman. Since superheavy nuclei close to the magic neutron number 184 could be long-lived and might be reached in the r-process, we also searched for primordial nuclei with mass numbers 292 ≤ A ≤ 310 in possibly homolog elements Os, Pb and “raw-platinum” from a South-African mine. In all cases we reached upper limits for the concentration ratio between 10^{-16} and 10^{-14}.

It should be mentioned in passing that AMS is also a powerful tool to detect α-emitting actinide nuclei in materials used for large-scale low-background detectors as was done for Cu, which is used in the holding structure of the GERDA double-beta experiment.

Material Science

Test of High Density 235U Fuel for the Research Reactor FRM II

The Munich FRM-II is a HEU-fueled (93% 235U) reactor used as a high flux neutron source. Due to the controversy over the use of 93% enriched uranium in the reactor, it was decided to transform to a fuel below 50% 235U enrichment. The most promising candidates to keep the 235U density in the fuel about the same but decrease enrichment are molybdenum uranium alloys where the total uranium density is increased. The alloy is either dispersed in an aluminum matrix or as a monolithic foil. TUM researchers uniquely simulate the radiation dam-

Figure 5. 60Fe concentration as a function of age for two different sediment cores from the equatorial Pacific [14].
age in such alloy systems by irradiating them at a dedicated irradiation setup with 80 MeV $^{127}$I beams up to an ion fluence of $2 \times 10^{17}$ cm$^{-2}$. Although neutron fluences are much larger during such a burn-up period it has been shown that the much stronger, non-linear effects related with thermal spike or Coulomb explosion from the high stopping power of the fission fragments challenge the material behavior [16]. In particular, interdiffusion layers are formed from which the materials are suffering. Irradiation of $^{235}$U-depleted material with $^{127}$I simulates within hours in-pile irradiations of months. In addition, no radioactivity is produced that hinders in-pile irradiated materials from standard materials testing procedures for several months.

**High Resolution Depth Profiling of Light Elements**

Our Q3D magnetic spectrograph (Figure 1) is not only an excellent tool for nuclear physics research, it has also unique capabilities in materials analysis using elastic recoil detection (ERD). Hereby, heavy ion beams like 170 MeV $^{127}$I or 40 MeV $^{197}$Au ions are guided under flat angles onto a thin film material to be analyzed. Recoil ions from Rutherford scattering events are analyzed by the Q3D at a scattering angle of 15° or by ΔE-E or TOF-E detectors placed at 40° in the scattering chamber of the Q3D with respect to the incident beam direction. The ERD-technique is in particular well suited to quantitatively analyze profiles of light elements in thin, μm thick films. While with standard detectors a depth resolution of about 10 nm is achieved, the Q3D allows sub-nanometer, in special cases even monolayer, depth resolution [17]. The applications are widespread in materials analysis: ultra-hard and optical materials, ultrathin semiconductor materials or even soft organic matter is analyzed. For example, it was used to determine the elemental composition of ultra-hard nanocomposites leading to a detailed model how the ultra-hardness is developed in such materials [18]. Another example is the analysis of unexpected bimodal range distributions of low energy carbon ions when depositing tetragonal amorphous carbon layers [19]. A very special application of ERD was the determination of the $^{10}$Be/$^{9}$Be ratio in a strongly activated sample, that was a major quantity to accurately measure the half-life of $^{10}$Be to 1.388(0.018) Ma, a common chronometer isotope to determine the age of materials formed on the surface of the earth [20].

**The Ion Microprobe SNAKE**

One of the main instruments used at the MLL tandem is the ion microprobe SNAKE (Superconducting Nanoprobe for Applied nuclear (Kern-) physics Experiments). It makes use of the high brightness ion beams delivered from the tandem accelerator, from protons to heavy ion beams, and a superconducting multipole lens. Sufficient beam can be focused to sub-micrometer beam spots in order to perform various kind of materials, radiobiology, and medical research. In particular, a multicusp ion source features hydrogen and deuterium beams up to 100 μA to be injected into the tandem resulting in a high beam brightness of 2 μA/(mm$^2$mrad$^2$MeV) at SNAKE.

**Hydrogen Microscopy**

Hydrogen is one of the main elements or an impurity element in nearly any kind of material determining chemical, mechanical, electrical, and optical properties. However, nearly all conventional microscopy techniques are not able to analyze lateral distributions of hydrogen in micrometer dimensions. Elastic proton–proton scattering utilizing 10–25 MeV protons at SNAKE overcomes several of these limitations. We have demonstrated a hydrogen detection limit below 0.1 at-ppm (<7 ppb weight) and a lateral resolution of better than 1 μm when analyzing hydrogen embedded in grain boundaries of polycrystalline diamond [21]. The high proton energies are necessary to analyze thin films up to a thickness of a few hundred micrometers since both scattered protons from elastic proton–proton scattering events are detected in transmission geometry.

The method has been applied to study thin, hydrogen loaded niobium films in view of a model hydrogen storage material deposited on 60 μm-thick silicon wafers. After loading the niobium films to an average atomic hydrogen concentration larger than 13 at% the film starts to lift off the substrate in μm-sized regions due to strong local stress while it remains stuck at others. The hydrogen content in the lifted areas increased to 40 at% while it remained at 13 at% on the parts of the film still fixed to the silicon (Figure 6) [22]. The measurement demonstrates the local separation of the two phases with different hydrogen content. It supports the so called Gorsky effect: due to local stress relaxation, hydrogen diffuses in the resulting gradients of chemical potentials forming the inhomogeneous hydrogen distributions.

Another application is the analysis of minerals from the inner earth mantle. Although they contain hydrogen below 100 at-ppm the integrated amount of hydrogen bound in the inner earth mantle via the minerals are much larger than the hydrogen bound in the oceans. The exact determination of hydrogen contents in these minerals is crucial to understand the mechanical and chemical behavior of the minerals under high pressure and temperature. Proton–proton scattering quantifies hydrogen contents even in small crystals ejected by volcanic activity independent of the analyzed matrix and is
used to calibrate standard minerals for commonly used infrared spectroscopy methods or SIMS analysis [23].

Radiobiology

The 10–20 MeV protons have a low linear energy transfer in water (LET < 10 keV/µm) while lithium or carbon ions from SNAKE show high LET. These ions focused to sub-micrometer diameter are ideally suited to target substructures of cells by counted ions and to directly compare the cellular reactions after low and high LET radiation. Irradiation takes place well defined in space, time, and local dose. Kinetics of cellular processes induced by the ions can be studied immediately after the irradiation event. SNAKE allows tackling long lasting questions in radiobiology and medicine:

What Enhances the Radiobiological Effectiveness (RBE) for Ions with High LET?

Alpha particles from radioactive sources or heavy ion beams require less dose to induce the same cellular reactions as low LET reference radiation, for instance X-ray. The ratio of the reference dose $D_{ref}$ to induce the same effect as the dose $D_{LET}$ of high LET radiation defines its RBE: $RBE = D_{ref} / D_{LET}$. In order to vary dose distribution on the micrometer scale we measured RBE enhancement for induction of dicentric chromosome aberrations of 20 MeV protons (LET = 2.6 keV/µm) by focusing a defined number of protons (e.g., 117 per point) to submicrometer beam spots in a grid pattern [24]. Thus, the dose distribution on the micrometer scale was artificially changed without changing the mean dose and the dose distribution on the nanometer scale (Figure 7). The data showed substantial enhancement of dicentrics induction for the grid-wise applied proton spots demonstrating the importance of interaction of DNA double strand breaks (DSB) on the micrometer scale. The data could be in part described by the Monte Carlo code PARTRAC that calculates dicentrics yields using physical dose distribution patterns and models for DNA damage and DNA damage interaction. Cell survival shows similar reduction by focused proton application that could be well fitted using the LEM IV model. The measurements show that the nm and µm scale of dose deposition and the sizes of cell nuclei of about 10 µm have to be taken into account to model the effects correctly.

Microscopic Analysis of Structure, Recruitment Kinetics, and Dynamics of Irradiation-Induced DNA Repair Foci

When inducing DSB most of them are well repaired by attracting repair factors accumulating in irradiation-induced foci. The recruitment kinetics changes for some of these factors depending on the ion’s LET while others do not change much [25]. The recruitment and also the movement of these foci can be followed by live cell online fluorescence microscopy at SNAKE when the repair factors are tagged by fluorescent dyes like green fluorescent protein. The dynamics in the movement of repair foci shows a subdiffusional $^{6,24}$ behavior for the distances between foci [26]. This leads to a high probability for the rejoining of the ends of a created DSB but also

![Figure 6](image6.png)

**Figure 6.** Micrograph of the buckled niobium film (a) analyzed for its local hydrogen content imaged by proton–proton scattering at SNAKE (b). The areas lifted off from the substrate show an average hydrogen content of (40 ± 5) at% as visible by the dark area of the hydrogen image while the areas that still stick on the substrate show a hydrogen content of (13 ± 2) at%.

![Figure 7](image7.png)

**Figure 7.** Repair foci (γ-H2AX) show various irradiation modalities that deposit a mean dose of 1.7 Gy: A grid-wise irradiation of 55 MeV gold ions ions (a), a random irradiation using 20 MeV (low LET) protons (b) and a grid-wise irradiation of 117 protons per point depositing the same amount of energy as a single 55 MeV ion (c).
to join the wrong ends if two DSB are situated within such a small distance while normal diffusion would result in a much lower probability in both cases.

The structure of the radiation-induced foci is studied using immunofluorescence and ultrahigh resolution fluorescence (stimulated emission depletion [STED]) microscopy showing fine structures of the different repair factors. Some of the repair factors anti-correlate although the foci colocalize on a gross scale (Figure 8) [27]. In addition, the fine structure of the repair foci was analyzed for their relative position to the chromatin structure showing their attraction at the rim of nanometer-sized chromatin domains.

Targeted microbeam irradiation at SNAKE is used to manipulate cellular substructures. We showed that the irradiation of mitochondria, the power stations of the cell, by high doses led to complete depolarization and inactivation visualized by the darkening of these mitochondria tagged with a polarization-sensitive stain (Figure 9) [28].

**Medical Research**

**Minibeam Proton Therapy**

Proton minibeam therapy is investigated for its potential to reduce side effects below that of conventional proton therapy (Figure 9). High energy proton beams are focused or collimated to submillimeter beam sizes and displaced by distances much larger than the beam sizes, leaving tissue between the minibeam with nearly no dose. The beam spreads on the way into the tumor where the beams overlap similar to conventional pencil beam scanning techniques. Thus, a homogeneous dose deposition is obtained in the tumor even if applying the minibeam from one side (Figure 9) [29]. Interlacing beams may also be used when using proton minibeam with even larger beam to beam separation from opposing sides such that tissue-sparing effects in the healthy tissue can be maintained up to close to the tumor.

Inflammation processes were compared after irradiating ears of living mice either by proton minibeam or proton beams of same mean dose of 60 Gy. Minibeam with a quadratic shape of $0.18 \times 0.18 \text{ mm}^2$ were formed at SNAKE and placed with inter-beam distances of 1.8 mm. While the broad beam irradiations showed strong inflammation reactions accompanied by weak ear swelling none of these reactions was obtained after proton minibeam irradiation (Figure 10). When comparing with broad X-ray irradiation of different dose the mean 60 Gy minibeam irradiation was less effective in induction of ear swelling than 10 Gy X-ray irradiation. Thus, minibeam irradiation opens new fields to further reduce side effects in healthy tissue but keeping tumor control.

The group of G.D. (UniBW) will install a 70 MeV post-accelerator to produce proton minibeam for further

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**Figure 8.** Fine structure of the repair proteins 53BP1 (violet) and Rad51 (green) imaged by STED fluorescence microscopy with a lateral resolution of ~100 nm after carbon (a) and proton (b) irradiation. The merged (I) as well as the single colours (II) and (III) are shown. The fine structure of the protein structures anticorrelate as quantified by a map of the reduced product of the differences from the mean (rPDM, IV) [27].

**Figure 9.** Dose distribution calculated for an extended Bragg peak to treat a hypothetic tumor situated 10 cm to 15 cm underneath the skin in case of conventional broad proton beam (upper graph) and proton minibeam (lower graph).
preclinical experiments. It will make use of an image guided small animal irradiation platform that is lead by K. Parodi (LMU) supported by an ERC grant.

In-Situ Proton Range Determination in Proton Therapy

Although proton and heavy ion beams induce much less ionizations in the healthy tissue compared to X-rays their full potential to spare healthy tissue cannot be used yet since range uncertainties in treatment planning require large safety margins that destroy somehow the advantageous dose distribution. An elegant way to determine the range of protons online is the use of ionoacoustics analyzing the traveling time of ultrasound signals that are generated mainly in the Bragg peak of microsecond pulsed proton beams (Figure 11). Better than 0.1 mm resolution of the Bragg peak position was demonstrated with 20 MeV proton bunches [30]. Even 3-D imaging of the Bragg peak position is possible [31]. An attractive option would be a direct integration into a conventional ultrasonic imaging system to obtain a relative measure between the Bragg peak and tumor position.

References

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**Figure 10.** Ear thickness of the right ear of bulb-c mice versus time after irradiation. The mean dose of the irradiated mouse ears was 60 Gy each.

**Figure 11.** Ionoacoustic signal from 16 ion pulses of 110 ns added from 2 × 10⁶ protons each transported through a thin kapton window into water. It shows the Bragg peak signal (1), a signal from the entrance window (2), and the Bragg signal reflected (3) from the kapton window traveling the proton range twice [30].

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Introduction

In the 1960s, quite soon after the recognition of the role of quantum shells in providing extra stability to nuclei, an “island of stability” of spherical superheavy nuclei was predicted. It was expected to be centered on proton number $Z = 114$ and neutron number $N = 184$, the next magic numbers predicted above $Z = 82$ and $N = 126$, which give nuclei around $^{208}\text{Pb}$ their enhanced stability. Since then, intensive experimental efforts have been made to synthesize these superheavy elements, usually defined as those with atomic number 104 or more. These have been very successful, leading to the recent formal announcement of the discovery and naming of the last four new elements required to complete the seventh row of the periodic table of the elements. These are nihonium ($Z = 113$), moscovium ($Z = 115$), tennessine ($Z = 117$), and the heaviest element yet discovered—ogaussen ($Z = 118$), named after Yuri Oganessian.

The mechanism of formation and the nuclear structure of superheavy elements (SHE) are key tests of quantum many body models, which are relevant to understanding neutron stars in astrophysics, and element formation and abundance in the Universe. Atom-by-atom measurements of superheavy element chemical properties are challenging, but allow testing of important relativistic effects in chemistry. Some of these measurements suggest that the periodicity of the chemical properties of elements with atomic number—the basis for Mendeleev’s periodic table of the elements—may to be coming to an end.

The position and extent of the “island of stability” of superheavy elements is still not certain. Modern theoretical predictions of magic proton numbers in the superheavy region are in the range 114 to 126. It seems likely that shell stabilization may occur across this region. This creates the possibility that isotopes of many new elements, heavier than those created up to now, will have lifetimes long enough to allow both nuclear and chemical properties to be experimentally determined. The problem then is how atoms of these elements can be synthesized.

The heaviest synthetic elements have all been created in collisions of two heavy nuclei, in which all the protons and neutrons of the colliding nuclei merge to form a new compact “compound” nucleus. Neutron evaporation from this excited compound nucleus competes with the predominant fission decay mode, occasionally resulting in the population of a superheavy nucleus in its ground-state. These are identified through a chain of characteristic decays. The sequence of six consecutive $\alpha$-decays within 47 seconds from copernicium-277 ($Z = 112$) was described by superheavy element pioneer Peter Armbruster as “a poem of physics.”

All the heaviest elements ($Z = 114$–118) have been formed in fusion reactions using beams of the doubly magic neutron-rich nucleus $^{48}\text{Ca}$ ($Z = 20$). Targets of elements heavier than Cf ($Z = 98$) cannot yet be made, as sufficient quantities of Es or Fm isotopes do not exist. To synthesize elements heavier than oganesson, heavier projectiles must therefore be used. Attempts to create $Z=119,120$ using heavier projectiles have not yet been successful, indicating that the production cross-sections are smaller than when using beams of $^{48}\text{Ca}$. Thus, a key question in superheavy element research is how much smaller SHE cross-sections will be when using beams of elements heavier than Ca. To make reliable model predictions, up to $Z = 126$, for example, the SHE formation process must be understood more thoroughly.

The shell stabilization of these heaviest elements is strong only for near-spherical shapes – the potential energy surface for more elongated shapes is repulsive. In fusion, the initial contact shape when two nuclei collide is elongated, being essentially that of the two touching nuclei. To create a SHE, this elongated shape must evolve to a compact near-spherical shape. However, this is resisted by the repulsive Coulomb-dominated potential. Consequently, a compact compound nucleus is rarely formed. Typically the initial kinetic energy is quickly damped, then the system performs a random walk over the repulsive potential energy surface, normally elongating and breaking apart into two heavy fragments. If the system breaks apart very quickly, there can be energy damping, but not enough time for significant mass evolution, and this is called a deep inelastic collision. If the system sticks together longer, the kinetic energy is fully damped, and some mass flow from the heavy to the light fragment occurs (as it moves toward more en-
ergetically favored mass-symmetric configurations) before it breaks apart. This non-equilibrium process is called quasi-fission \[1, 2\]. It can result in a drastic suppression of the SHE formation cross-section.

Quasi-fission can occur very rapidly \[2, 3\], typically in less than \(10^{-20}\)s (10 zeptoseconds). The probability of quasi-fission (\(P_{QF}\)) can be very large, thus the complementary probability of fusion forming a compact compound nucleus (\(P_{CN} = 1 - P_{QF}\)) can be small, probably lower than \(10^{-3}\) in reactions forming the heaviest elements. Understanding and predicting the competition between quasi-fission and fusion is thus very important in mapping out the optimal fusion reactions to use in future to synthesize new elements and isotopes in the superheavy mass region. The most direct information on quasi-fission dynamics comes from measurements of the characteristics of the quasi-fission events themselves. Clearly, predictive models of superheavy element synthesis reactions should be able to describe measured quasi-fission characteristics (and how these change with different choices of colliding nuclei) as well as reproduce existing \(P_{CN}\) values determined through model-independent measurements of heavy element formation cross-sections \[4, 5\].

A key characteristic relevant for superheavy element formation is the “sticking time” following contact of the two nuclear surfaces. It is expected that the sticking time is correlated with \(P_{CN}\); where the sticking time is longer, then \(P_{CN}\) would be expected to be larger (more favorable for SHE synthesis) The average sticking time can be inferred from measurements of the quasi-fission characteristics, as illustrated in Figure 1. The two colliding nuclei always approach each other along the beam axis, and after contact rotate with angular velocities that can be calculated \[6\]. Measurement of the rotation angle thus allows estimation of the sticking time. As the system rotates, mass flow also occurs between the two nuclei. Measurement of the velocity vectors of both fragments \[2, 7\] provides excellent discrimination against fission of target-like nuclei resulting from peripheral (e.g., nucleon transfer) processes \[7, 8\], and furthermore allows determination of the center-of-mass angle and mass-ratio \(M_R = M_1/(M_1 + M_2)\) of the fragments at scission (here \(M_1, M_2\) are the fragment masses).

Measurements of \(M_R\) over a wide range of angles is called a mass-angle distribution (MAD). This gives direct information on the dynamical time scales, as long as the system undergoes less than a full rotation (taking \(\sim 10^{-20}\)s). This is usually the case for collisions of heavy nuclei, as shown first by measurements at GSI \[2\], and later by results from ANU \[3, 8–10, and references therein\].

Examples of measured MAD and deduced quasi-fission sticking time distributions are shown in Figure 2, for reactions forming the compound nucleus \(^{234}\text{Cm}\) \[9\]. MAD can be most simply characterized \[8\] into three categories having: (i) a mass-angle correlation with a minimum yield at mass-symmetry—associated with short sticking times (MAD1, shown in Figure 2a); (ii) a mass-angle correlation with maximum yield at mass-symmetry—from intermediate sticking times (MAD2, shown in Figure 2b); and (iii) no significant mass-angle correlation and a narrow mass-distribution—associated with long sticking times, including fission following fusion (MAD3, shown in Figure 2c).

![Figure 1. The principles underlying the mass-angle distribution (MAD).](image)

Figure 1. The principles underlying the mass-angle distribution (MAD). (Top left) The sequence of configuration changes after initial contact of light (blue) and heavy (red) nuclei, here with an initial center-to-center angle at contact of 160°. (a) and (b) show rotation and mass-equilibration (in terms of mass-ratio \(M_R\)) as a function of time (\(10^{-21}\)s). These times cannot be measured directly; however, mass-ratio and angle can be measured. One trajectory in mass-ratio and angle is illustrated in (c), the orange highlighted region indicating the region of collision outcomes resulting from a short sticking time and rapid separation (scission).
The systematic trends of MAD characteristics with the identity of the two colliding nuclei was studied [8], to determine global trends of quasifission dynamics. This is in analogy with the evaluation of the liquid drop model dependence of nuclear masses on N and Z, where deviations from smooth behavior highlight the effects of nuclear structure. Choosing bombarding energies E well above the mean capture barrier B (around E/B = 1.08), nuclear structure effects were minimized. It was found [8] at these bombarding energies that the MAD are indeed strongly correlated with global variables. The simplest variables are the Coulomb repulsion in the entrance channel (related to the product of the proton numbers of the projectile and target nuclei $Z_pZ_t$), and the compound nucleus atomic number $Z_{CN}$, as illustrated in Figure 3. However, for particular reactions, it has been found that the nuclear structure of the nuclei in the entrance channel can change the sticking times and MAD characteristics dramatically. This is clearly seen for doubly magic neutron-rich nuclei such as $^{48}$Ca and $^{208}$Pb, and prolate deformed nuclei (all used in SHE formation reactions), as described below.

**Static Deformation**

The effect of static deformation of the heavy reaction partner on the reaction dynamics has been clearly shown
in the dependence of the MAD characteristics with beam energy from below to above the average capture barrier energy \(B\) [10]. For deformed nuclei, at energies below \(B\), the reduced Coulomb repulsion for contact on the tips [6] allows capture for elongated (deformation aligned) configurations only, as illustrated schematically on the right side of Figure 4. To the left, experimental mass widths for reactions of \(^{48}\text{Ti}\) with a range of heavy nuclei are shown, extending from \(^{144}\text{Sm}\) (spherical) through \(^{154}\text{Sm},\ 174\text{Yb},\ 192\text{Os}\) (all prolate deformed) to \(^{208}\text{Pb}\) (spherical). For deformed heavy nuclei, large mass widths are found at below-barrier energies \((E/B < 1)\) corresponding to MAD of type 2 (Figure 2). At \(E/B > 1\), narrowing mass widths show the increasing contribution from more compact equatorial con-
tact configurations, resulting in longer sticking times and mass distributions closer to symmetry.

Already in 1995, interpretation of experimental fission measurements from below to above-barrier led to the suggestion [11] that deformation alignment should be important in SHE synthesis—and indeed, it has been observed that using prolate deformed actinide nuclei, SHE are not created where \( E/B < 1 \). This contrasts with reactions of spherical nuclei.

In reactions of heavier projectiles with prolate deformed actinide nuclei, such as \( ^{238}\text{U} \), the difference in observed MAD between the elongated, deformation-aligned contact configurations found below-barrier, and the more compact equatorial collisions is even greater [13]. This is illustrated in Figure 5 for the reaction \( ^{40}\text{Ca} + ^{238}\text{U} \). The sub-barrier measurement shows a MAD of type 1, with time scale ~5 zs. Above-barrier, mass-symmetric events become increasingly probable, associated with compact contact configurations and longer sticking times.

Microscopic quantal mean-field TDHF calculations [14] were carried out for this reaction for two extreme orientations: deformation-aligned (axial) and equatorial collisions. The axial collisions had a sticking time typically 6 zs, almost independent of angular momentum. Furthermore the \( Z, N, \) and \( A \) of the quasifission fragments from axial collisions showed little variation with angular momentum, excitation energy, or with sticking time, being centered on 82, 122, and 204, respectively. This suggests that the \( Z, N \) closed shells around \( ^{208}\text{Pb} \) are important in the TDHF calculations. Since they show good agreement with the experimental MAD, this implies that shell effects are playing an important role in quasifission dynamics. In the calculations, equatorial collisions for low impact parameters do not re-separate within 25–40 zs, and are taken as resulting in fusion, and subsequent fusion-fission. The higher impact parameter equatorial collisions have sticking times and mass-ratios strongly dependent on angular momentum.

For a given sticking time, the equatorial collisions generally experience more mass-equilibration than the axial collisions, suggesting a special role of the \( ^{208}\text{Pb} \) double closed shell in limiting the mass flow to symmetry in the axial collisions. However, experimentally the mass-asymmetric peaks resulting from axial collision are quite broad, inconsistent with the narrow potential valley near \( ^{208}\text{Pb} \). Thus it may be that the effect of the \( ^{208}\text{Pb} \) structure on the mass distributions has a dynamical origin, and the mechanism, including the effect of fluctuations, needs more investigation.

**Spherical Magic Nuclei**

Sub-barrier collisions involving heavy (spherical) closed-shell nuclei show contrasting behavior to those with heavy statically deformed nuclei. This is highlighted in Figure 4, where the mass width for the \( ^{48}\text{Ti} + ^{208}\text{Pb} \) reaction falls strongly as the beam energy drops, in contrast to the lighter deformed nuclei, where it rises steeply.

To investigate in detail the effect of closed shells in the entrance channel on quasifission probabilities and characteristics, measurements [15] of MAD were made for \( ^{40,44,48}\text{Ca} \) projectiles bombarding targets of \( ^{208,204}\text{Pb} \) (forming \( ^{248,252}\text{No} \) with \( Z_{\text{C.N.}} = 102 \)), and for \( ^{48}\text{Ti} \) bombarding \( ^{200}\text{Hg} \) (\( ^{248}\text{No} \)) and \( ^{208}\text{Pb} \) (\( ^{256}\text{Db} \) with \( Z_{\text{C.N.}} = 104 \)). Measurements were made a few percent below the average fu-

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**Figure 6.** Measured MAD for the indicated reactions at \( E/B = 0.98 \) (upper panels). In the projected mass ratio spectra (lower panels) the scale factor multiplies the counts scale. Gaussian functions with \( \sigma_{MR} = 0.07 \) (thin red lines) are shown for reference. Gaussian fits to the region around \( M_R = 0.5 \) (turquoise lines), whose standard deviations \( \sigma_{MR} \) are tabulated, along with the total number of magic numbers of the projectile and target nuclei \( N_{\text{Magic}} \), and the difference \( \Delta(N/Z) \) between the projectile and target nucleus \( N/Z \) ratios. Adapted from Ref. [15], with new ANU data for \( ^{48}\text{Ca} + ^{208}\text{Pb} \).
sion barrier energy to give “gentle” collisions with minimal relative velocity at contact.

The MAD and projected $M_R$ spectra are shown in Figure 6, together with reference data for the $^{16}$O + $^{238}$U reaction at an above-barrier energy, which forms $^{254}$Fm. The standard deviations $\sigma_{MR}$ of the Gaussian fits are tabulated. Despite having similar or identical $Z_pZ_t$ and forming similar or identical compound nuclei, values of $\sigma_{MR}$ differ by more than a factor of three, indicating a significant variation in the characteristics and probability of quasi-fission. Indeed, for the $^{48}$Ca + $^{208}$Pb reaction, mass distribution widths appear consistent with a fusion-fission mechanism. To understand this, the correlation of $\sigma_{MR}$ with the sum of the number of magic numbers in the projectile and target nuclei $N_{Magic}$ is informative [15]. Large values of $\sigma_{MR}$ are found for no magic numbers, reducing to values expected for fusion-fission for maximal $N_{Magic}$ (for $^{48}$Ca + $^{208}$Pb). This suggests that reactions involving nuclei having several magic numbers form a compact compound nucleus with higher probability. It seems likely that this is associated with reduced energy dissipation as the two nuclei come together, allowing more compact shapes to be reached. The difference between the $N/Z$ values of the target and projectile nuclei are also shown, denoted by $\Delta(N/Z)$. The correlation of $\sigma_{MR}$ with $\Delta(N/Z)$ shows that “magicity” plays its strongest role when the $N/Z$ values of the projectile and target nuclei are well-matched. When this is not the case, transfer reactions even before contact are expected to change the identity of the nuclei, and thus attenuate the entrance-channel magicity, as seen for the $^{40}$Ca + $^{208}$Pb reaction [15].

More recent ANU quasifission results, for the reaction of isotopes of Cr with Pb, support these conclusions regarding both magicity and $N/Z$ matching. MAD and mass-ratio projections at a sub-barrier energy for each reaction studied are shown in Figure 7. The three reactions on the left all form the same compound nucleus $^{258}$Sg. The panels are ordered from left to right, first by the number of magic numbers in the entrance channel $N_{Magic}$, and then by $\Delta(N/Z)$. The left-most reaction has only a single magic number in the entrance channel, and shows a U-shaped mass distribution, consistent with the MAD1 category. In the representation of systematics in Figure 3, these reactions lie at the position of the right-most purple circle, thus a mass distribution with a minimum in yield at symmetry would indeed be expected. With two magic numbers, the reactions better matched in $N/Z$—smaller values of $\Delta(N/Z)$—show a peak at mass-symmetry, associated with an angle-independent ridge in the MAD. This corre-

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**Figure 7.** Experimental MAD and projected mass-ratio spectra ($90^\circ < \theta_{c.m.} < 135^\circ$) for sub-barrier ($E/B \sim 0.98$) collisions of $^{50,52,54}$Cr isotopes with $^{204,206,208}$Pb, with the excitation energies $E^*$ indicated. Both $N_{Magic}$ and $\Delta(N/Z)$ are indicated for each reaction, as in Figure 6. Reactions with more magic numbers and more favorable $\Delta(N/Z)$ display an angle-independent mass-symmetric fission component (purple line for $^{52}$Cr + $^{206}$Pb), suggestive of fusion-fission. The superimposed red Gaussians represent the measured mass-width for the $^{48}$Ca + $^{208}$Pb reaction.

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The panels are ordered from left to right, first by the number of magic numbers in the entrance channel $N_{Magic}$, and then by $\Delta(N/Z)$. The left-most reaction has only a single magic number in the entrance channel, and shows a U-shaped mass distribution, consistent with the MAD1 category. In the representation of systematics in Figure 3, these reactions lie at the position of the right-most purple circle, thus a mass distribution with a minimum in yield at symmetry would indeed be expected. With two magic numbers, the reactions better matched in $N/Z$—smaller values of $\Delta(N/Z)$—show a peak at mass-symmetry, associated with an angle-independent ridge in the MAD. This corre-

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**Table 1.** Values of $N_{Magic}$ and $\Delta(N/Z)$ for the reactions shown in Figure 7.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$N_{Magic}$</th>
<th>$\Delta(N/Z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{54}$Cr + $^{204}$Pb</td>
<td>1</td>
<td>0.24</td>
</tr>
<tr>
<td>$^{50}$Cr + $^{206}$Pb</td>
<td>2</td>
<td>0.45</td>
</tr>
<tr>
<td>$^{52}$Cr + $^{206}$Pb</td>
<td>2</td>
<td>0.35</td>
</tr>
<tr>
<td>$^{54}$Cr + $^{208}$Pb</td>
<td>2</td>
<td>0.29</td>
</tr>
<tr>
<td>$^{52}$Cr + $^{208}$Pb</td>
<td>3</td>
<td>0.37</td>
</tr>
</tbody>
</table>
sponds to very long sticking times, perhaps even fusion-fission. With three magic numbers, but less favorable $\Delta$N/Z, a similar result is observed.

These reactions show the same dependence on magic numbers and N/Z matching as the $^{40,44,48}\text{Ca} + ^{204,208}\text{Pb}$ reactions. However, the transition from a U-shaped mass distribution to a narrow distribution peaked at mass-symmetry, with no evidence for a mass-angle correlation, is a very drastic change in reaction outcome. This is direct evidence of a major bifurcation in reaction trajectories for a given reaction, which is less obvious in the Ca + Pb MADs. Figure 3 indicates that in reactions forming Sg, a MAD of class 3 would be expected for $Z_pZ_t < 1200$ (left-most purple circle), in the absence of the favorable effect of magic numbers. This would correspond to a reaction with an Al projectile or lighter, with around half the atomic number of Cr. The dramatic change in reaction outcome with a small change in neutron number indicates that the observed systematic behavior at higher beam energies does not necessarily allow prediction of behavior in near-barrier reactions, where the nuclear structure of the system can play a very significant role (as is also the case in the characteristics of spontaneous and low energy nuclear fission).

It is clear that both static deformation and spherical magic numbers in the colliding nuclei can play a major role in determining the sticking time in a collision. This ranges from rapid reseparation with only a small change in mass, to sticking together so long that the fission characteristics are those of fusion-fission.

Future Prospects

To provide a deeper understanding of fusion of heavy nuclei, and of SHE synthesis reactions in particular, measurement of quasifission MADs for a range of projectile and target combinations (projectiles from $^{48}\text{Ca}$ to $^{64}\text{Ni}$, and targets from $^{208}\text{Pb}$ to $^{249}\text{Cf}$) are underway at the Australian National University, in collaboration with researchers from GSI and Mainz. They will add to extensive measurements [16] of mass and total kinetic energy correlations for fragments emerging around 90° in the center of mass frame. These new data should provide important information on the time-dependence of the quasifission observables.

The very sudden changes seen in quasifission characteristics, depending on magicity, neutron number, and beam energy will be a severe challenge for models of quasifission and SHE formation to reproduce. And yet it is this level of sensitivity of reaction dynamics to nuclear structure that models must strive to reproduce, to map out the optimum experimental opportunities to create new superheavy elements and isotopes in the future.

Acknowledgments

Experiments were carried out at the Australian National University Heavy Ion Accelerator Facility. All nuclear reaction dynamics group members are gratefully acknowledged for their contributions to experiments, data analysis, and interpretation. This work has been supported by several Australian Research Council Grants (DP140101337, DP160101254, SP170102318, DE140100784, FT120100760, and FL110100098) and accelerator operations support from the Australian Federal Government NCRIS program.

References


Filler
The OLYMPUS Experiment at DESY

Introduction

It has been about 100 years since Ernst Rutherford named the hydrogen nucleus the proton, which was later discovered to be a fundamental component in all nuclei. Yet many fundamental parameters of the proton are still not completely understood and still excite both theoretical and experimental research. The proton radius [1], the proton spin [2], and how the proton mass arises from the energy of the constituent and current quarks in lattice QCD [3] are all still topical subjects in nuclear physics. The OLYMPUS experiment addressed yet another “proton puzzle” concerning the ratio of the charge and magnetic form factors.

Electron scattering has long been a standard technique for studying nucleons and nuclei. The electromagnetic interaction is well understood and the point-like nature of electrons make them ideal for probing electric and magnetic charge distributions. Historically, unpolarized electron-proton scattering has been analyzed in terms of one-photon exchange (Born approximation) to determine the electric, \( G_E^p \), and magnetic, \( G_M^p \), form factors for the proton. But recent experiments with polarized electrons, polarized targets, and measurements of the polarization transferred to the proton are in striking disagreement with the unpolarized results (Figure 1). The unpolarized results, obtained using the Rosenbluth technique, are known to be insensitive to the electric form factor, \( G_E^p \), at high momentum transfer while the polarization measurements make a direct measurement of the form factor ratio, \( \mu_p G_E^p/G_M^p \), by measuring the ratio of transverse to longitudinal nuclear polarization (see Ref. [4] for references). But how do we reconcile the discrepancy between the two techniques?

Radiative corrections must be applied to the measured cross-sections to extract the equivalent one-photon exchange value so results from different experiments and theoretical calculations can be compared. These radiative corrections can be significant and are complicated by details of the experimental acceptance, efficiency, and resolution. But radiative corrections might be the key to resolving the observed discrepancy. A more complete handling of two-photon exchange contributions has been suggested as a possible explanation (Figure 2). Two-photon exchange is generally included in the standard radiative corrections but only in the “soft” limit where one of the photons imparts negligible energy to the proton. Such calculations are generally independent of models for the proton structure. “Hard” two-photon exchange is more difficult to calculate because details of the proton

![Figure 1. Proton form factor ratio, \( \mu_p G_E^p/G_M^p \), from unpolarized measurements shown in blue and polarized measurements shown in red.](image-url)
ground state and nucleon resonances for the intermediate state must also be considered.

To determine the contribution of “hard” two-photon exchange the OLYMPUS experiment proposed to measure the ratio of positron–proton to electron–proton elastic scattering. If two-photon exchange is a significant factor in lepton–proton scattering the ratio will deviate from unity because the interference between one- and two-photon exchange changes sign between electron and positron scattering. Naively, one would expect a small effect of order $\alpha \approx 1/137$ but that would not explain the striking discrepancy observed in the proton form factor ratio.

DORIS Storage Ring

The OLYMPUS experiment [4] ran on the DORIS storage ring at the DESY Laboratory in Hamburg, Germany. DORIS began operation in 1974 as an electron–positron collider for particle physics experiments. In 1981, it was also developed as a synchrotron light source for the HASYLAB facility, which became the sole function for DORIS after 1993 until October 2012. But DORIS retained the ability to store both electrons and positrons. This capability was crucial for the OLYMPUS experiment, which switched daily between beams of electrons and positrons.

DESY undertook significant modifications to the DORIS storage ring to accommodate the OLYMPUS experiment. RF cavities and quadrupoles had to be relocated from the straight section of the storage ring where OLYMPUS was to be located. Services for cooling water and power for the OLYMPUS toroidal magnet had to be installed and the shielding walls extended to make room for the detector. The power supplies for the DORIS ring were also modified so their polarity could be changed quickly when switching between positron and electron running. A large transport frame was also produced to support the OLYMPUS detector on rails. This allowed the detector to be assembled outside the ring and then rolled into the ring for the experiment. At the end of 2012 DORIS ran in “top-up” mode to deliver a steady, high intensity current to achieve the luminosity OLYMPUS needed.

The OLYMPUS experiment installed a hydrogen gas target internal [5] to the storage ring (Figure 3). The target consisted of a thin-walled, elliptical tube 600 mm long without entrance or exit windows. Hydrogen gas was injected into the center of the tube and allowed to diffuse to either end where a series of vacuum pumps were used to maintain the high vacuum required by the storage ring. The nominal target areal density was approximately $3 \times 10^{15}$ atoms/cm$^2$. Additionally, the target region required

**Figure 2.** Feynman diagrams for one- and two-photon exchange contributions to lepton–proton scattering. Other radiative corrections (not shown) arising from bremsstrahlung, vertex corrections, self-energy, and vacuum polarization diagrams must also be included in calculations.

**Figure 3.** OLYMPUS target cell in the scattering chamber. The target cell is elliptical to accommodate the beam halo profile. Also shown are the wakefield transition pieces.
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Figure 4. Schematic of the OLYMPUS detector with the top magnet coils removed to show the horizontal sector holding the detectors. The drift chambers are shown as three separate chambers in each sector but are actually combined to form a single gas volume.

collimators to shield against synchrotron radiation and specially designed transition pieces to minimize wakefield effects.

OLYMPUS Experiment

In 2010, the former BLAST detector [6] from MIT-Bates was disassembled and shipped to DESY where it was reassembled. The detector (Figure 4) consisted of an eight-sector toroidal magnetic spectrometer with the two horizontal sectors instrumented with drift chambers covering polar, \(20^\circ \leq \theta \leq 80^\circ\), and azimuthal, \(-15^\circ \leq \phi \leq 15^\circ\), angles for 3D particle tracking together with walls of time-of-flight scintillator bars for triggering and particle identification. The detector was left-right symmetric and this was used as a cross-check during the analysis.

Two new detector systems were built to monitor the luminosity. These were symmetric Møller/Bhabha calorimeters at \(\theta = \pm 12^\circ\) in the horizontal plane.

The timeline for the OLYMPUS experiment was very tight. OLYMPUS received approval and funding in December 2009 and faced a fixed deadline of December 2012 when DORIS was scheduled to be shut down. The detector rolled into the DORIS ring in July 2011. After a few commissioning tests, it ran for one month in February 2012, and then for two months at the end of 2012, alternating daily between electrons and positrons at 2.01 GeV with a typical current around 65 mA. In total OLYMPUS collected approximately 4.5 fb\(^{-1}\) of data, 25% more than the original proposal.

Analysis Results and Discussion

The analysis of the OLYMPUS experiment [7] was complicated by an inhomogeneous magnetic field and drift chamber inefficiencies due to the high rate of Møller and Bhabha electrons that were bent into the innermost drift chambers. Originally it was planned to change the toroid magnet polarity each day to reduce tracking systematics but the background with negative polarity prevented operation at high currents so the OLYMPUS data currently analyzed is with positive polarity only. To

Figure 5. OLYMPUS results compared to calculations from Blunden, Bernauer, and Tomalak. The inner error bars correspond to statistical uncertainty while the outer bars include uncorrelated systematic uncertainties added in quadrature. The grey band indicates correlated systematic uncertainties.
properly analyze the OLYMPUS data, a detailed Monte Carlo simulation was written using GEANT4. This allowed the Monte Carlo simulation to account for the differences between electrons and positrons with respect to radiative effects, changing beam position and energy, the spectrometer acceptance, track reconstruction efficiency, luminosity, and elastic event selection. The resulting ratio for the positron–proton to electron–proton cross-sections was then determined by calculating:

$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}} = \frac{N_{\text{exp}}(e^+) / N_{\text{MC}}(e^+)}{N_{\text{exp}}(e^-) / N_{\text{MC}}(e^-)}$$

where the $N_i$ are luminosity normalized experimental and Monte Carlo yields.

The OLYMPUS results are shown in Figure 5 together with various calculations [8–10]. The results are below unity at low $Q^2$ (high $\epsilon$) but tend to rise with increasing $Q^2$ (decreasing $\epsilon$). The dispersive calculations of Blunden, which can account for part of the discrepancy observed in the form factor ratio at higher $Q^2$, are systematically above the OLYMPUS results in this energy regime. The phenomenological prediction from Bernauer and the subtractive dispersion calculation from Tomalak (that also uses Bernauer’s fit to the form factor data) are in reasonable agreement with the OLYMPUS results.

Two other recent experiments, VEPP-3 [11] and CLAS [12], also measured the ratio of positron–proton to electron–proton scattering to determine the contribution of two-photon exchange to elastic lepton scattering. However, it is difficult to compare these results directly with OLYMPUS since their measurements were performed at different energies with results at different points in the $(\epsilon, Q^2)$ plane. To partially account for this, we can compare all the two-photon exchange results by taking the difference with respect to a theoretical calculation (in this case Blunden’s $N + \Delta$ calculation) evaluated at the correct $(\epsilon, Q^2)$ for each data point. This is shown in Figure 6 plotted versus $\epsilon$.

In this view, the results for $R_{2\gamma}$ from the three experiments are seen to be in reasonable agreement with each other over the range in $\epsilon$ but are systematically below the theoretical calculation. This supports the previous assertion that the theoretical calculation overestimates the results in this energy regime. However, the $\epsilon$ dependence of both the results and calculations appears to be in agreement.

**Conclusions**

At the momentum transferred range measured by OLYMPUS the effect of “hard” two-photon exchange is small, on the order of 1%. This is good news for historical electron scattering measurements made at low energies but does not explain the observed discrepancy in the form factor ratio at higher energies. The rising trend in the ratio $R_{2\gamma}$ with increasing $Q^2$ (decreasing $\epsilon$) may indicate that two-photon exchange is present and may become significant at higher energies. However, to prove this will require measurements at higher energies that will be difficult due to the rapid decrease in the cross-section.

Current theoretical calculations that explain part of the observed discrepancy at higher energies overestimate the effect at the energies measured by the three recent experiments. Possibly higher order radiative corrections are required or nucleon states beyond the $N + \Delta$ need to be considered.

The discrepancy in the form factor ratio measured using unpolarized and polarized techniques and the possible role played by two-photon exchange continues to be topical within the nuclear physics community [13]. A parallel session at the NSTAR 2017 Workshop [14] will be devoted to two-photon exchange. Also, the need for future experiments at higher energy have stimulated discussions at JLab [15] as well as other laboratories. A review of two-photon exchange in elastic electron-proton scattering will also be published soon [16].

![Figure 6. Difference between the three recent two-photon exchange experimental results and the theoretical $N + \Delta$ calculation from Blunden.](image-url)
more theoretical and experimental work will bring a better understanding of the proton’s structure in the near future.

Acknowledgments
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References
Ever higher demands on resolution and rate capability drive the development of particle tracking detectors. Especially at low momenta, multiple Coulomb scattering in the material of the detector is also strongly affecting the resolution of momentum measurements. While gas-based detectors such as drift chambers and time projection chambers can be built with very small amounts of material, their rate capability is limited by ageing and space charge effects. Hybrid semiconductor detectors on the other hand combine a depleted (silicon) sensor with a custom amplifier and readout chip. Pixelated devices especially can operate efficiently in very harsh rate and radiation environments such as the innermost parts of the general purpose LHC experiments. The large amount of material introduced by two semiconductor devices connected by a bump bond for each pixel, however, precludes precise tracking of low momentum particles.

If the sensor and the readout electronics are combined in the same device, we speak of monolithic active pixel sensors MAPS. These devices can be thinned to ~50 µm and are thus well suited for building low-mass tracking detectors. The most prominent example are the MIMOSA sensors [1] employed, for example, in STAR [2], the ALICE upgrade [3], and the EUDET beam telescopes [4]. Their main drawback is the relatively slow charge collection via diffusion and low radiation tolerance.

HV-CMOS monolithic active pixel sensors (HV-MAPS) are the first depleted pixel sensor technology that is based on an industrial CMOS (complementary metal oxide semiconductor) process with no structural modifications. These sensors are based on recent developments in chip manufacturing that provide deep wells that can house the electronics and isolate them from the chip substrate. This allows biasing of the substrate with high voltages around 100 V leading to a depletion zone underneath the well with a large field and fast charge collection via drift. Inside the wells, CMOS electronics for amplifiers, comparators, and data processing can be implemented. The wells themselves act as charge collecting electrodes. See Figure 1 for a schematic view of high voltage monolithic active pixel sensors (HV-MAPS, [5]). The use of a standard process assures low cost and a large choice of foundries that can produce these sensors.

The success of HV-MAPS motivated development of numerous sensor flavors with similar structures. All these sensors include amplifier and readout electronics on depleted silicon and are in general known as depleted MAPS or DMAPS. A variety of technologies with different substrate resistivities, different deep wells, and different post-processing (e.g., backside contacts) is currently under evaluation in terms of signal to noise ratios, power consumption, and radiation hardness [6]. HV-MAPS based on an AMS 180 nm HV-CMOS process are arguably the most advanced DMAPS prototypes with very extensive experience from laboratory and beam tests as well as integration into beam telescope systems.

An excellent use case for HV-MAPS is the Mu3e experiment at PSI [7], which intends to search for the lepton-flavor violating decay $\mu^+ \rightarrow e^+ e^- e^-$ aiming for a sensitivity of 1 in $10^{16}$ muon decays. This requires tracking the decay products of over a billion stopped muons per second with very high accuracy to keep backgrounds under control. The maximum electron/positron momentum is just 53 MeV/c, thus multiple Coulomb scattering dominates the momentum resolution achievable in the 1 T solenoid spectrometer [8]. Minimizing material is thus absolutely crucial: Using aluminium-polymide flexprints both for electrical connectivity and mechanical support and a high flow helium gas

Figure 1. Schematic view of a HV-CMOS sensor. The p-substrate is reversely biased with regard to the deep n-wells, creating a thin depletion region with a large field and very fast charge collection. Amplifier electronics are implemented inside the deep n-well. From Ref. [5]. Reprinted from Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 845, H. Augustin et al., The MuPix system-on-chip for the Mu3e experiment, 194–198, Copyright (2016), with permission from Elsevier.
cooling we can build tracking layers with a thickness of roughly a permille of a radiation length [9].

In the context of the Mu3e experiment, we have designed, produced, and characterized a series of HV-MAPS prototypes, the MuPix chips (see Figure 2 for a microscope photo). The latest fully characterized version, MuPix7, includes the complete system-on-a-chip required for the experiment [10]: A matrix of $103 \times 80$ µm$^2$ pixels with an in-pixel amplifier, a periphery with a second amplifier and a comparator for each pixel and time-stamping mechanism. Readout electronics controlled by a state machine collect the addresses and timestamps of hit pixels and sends them off-chip using a low-voltage differential signaling link that can be operated at up to 1.6 Gbit/s. With this scheme, we can successfully go from particle detection to fully digital on a single device with just 50 µm thickness. As every pixel is its own readout cell, the device as a whole is almost dead-time free.

We have characterized the MuPix7 using charge injection, lasers, and radioactive sources in the lab and at various beam tests at DESY, PSI, CERN, and MANI in Mainz. For 4 GeV/c electrons at DESY as well as a 250 MeV/c mixed pion, muon, and positron beam at PSI, we have found efficiencies above 99.5% for noise rates well below 10 Hz per pixel (Figure 3). The position resolution for our digital readout is given by the pixel size divided by $\sqrt{12}$. The time resolution relative to a scintillator reference is 11 ns (RMS), dominated by time-walk (Figure 4).

MuPix7 has an active area of $3 \times 3$ mm$^2$; for the final sensor we require $20 \times 20$ mm$^2$. The next prototype, MuPix8, thus features the full column length of 20 mm and also incorporates a charge measurement, allowing for a time-walk correction and thus a much-improved time resolution. MuPix8 is being tested at the time of writing and the first lab results are very promising.

The fast charge collection from a very small region also promises very good radiation hardness of the technology. The new MuPix8 sensor in addition employs radiation-hardened transistor layouts and as such can be used also in experiments where radiation tolerance is required. While not decisive for Mu3e, this is of great interest for other use cases such as the ATLAS upgrade [11]. Radiation tolerance as required for ATLAS has been demonstrated with test HV-CMOS sensors without readout called CCPD (capacitively coupled active pixel sensors) [12]. These sensors already use the radiation-hardened version of the MuPix electronics. First results with MuPix7 sensors irradiated with high fluences of protons or neutrons are also very promising.

HV-MAPS have attracted a lot of interest from experiments across the fields of particle, hadron, and nuclear physics. The luminosity detector of the PANDA experiment at FAIR will be based on HV-MAPS operated in vacuum and cooled via diamond support wafers [13]. The parity violation experiment P2 [14] at the new MESA accelerator in Mainz will use a HV-MAPS-based tracker in order to deal with several GHz of electron tracks in the acceptance. Telescopes of HV-MAPS detectors are under study for use in Compton polarimetry at JLAB and in an electron proton scattering experiment using a high-pressure hy-

![Figure 2. Microscope view of the corner of a thinned (50 µm) MuPix prototype. The bright structures are 50 µm by 50 µm bond pads. The pixel matrix is under the long power distribution lines in the top right.](image)

![Figure 3. Efficiency and noise level of the MuPix7 prototype as determined using a 250 MeV/c mixed pion, muon and positron beam at PSI. From Ref. [10]. Reprinted from Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 845, H. Augustin et al., The MuPix system-on-chip for the Mu3e experiment, 194-198. Copyright (2016), with permission from Elsevier.](image)
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Figure 4. Time resolution of the MuPix 7 prototype determined in a 4 GeV electron beam at DESY using 16 ns time stamps. From Ref. [10]. Reprinted from Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 845, H. Augustin et al., The MuPix system-on-chip for the Mu3e experiment, 194–198, Copyright (2016), with permission from Elsevier.

hydrogen time-projection-chamber at MAMI in Mainz. A MuPix telescope is also routinely used as a reference for detector tests at MAMI [15]. And last but not least, HV-MAPS are considered for the ATLAS upgrade and the detectors at the compact linear collider CLIC.

Acknowledgments

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The “Beta-Delayed Neutrons at RIKEN” Project (BRIKEN): Conquering the Most Exotic Beta-Delayed Neutron-Emitters

Among the main missions of modern radioactive isotope facilities is the exploration of properties of yet unknown isotopes on the neutron-rich side of the chart of nuclides. However, going more neutron-rich also means that the neutron separation energy decreases until it reaches the dripline at $S_n = 0$ MeV. If the neutron separation energy gets lower than the $\beta$-decay energy window ($Q_\beta$ value), a new decay mechanism can occur: the emission of neutrons after $\beta$-decay. These “$\beta$-delayed neutron” ($\beta n$) emitters play a crucial role in nuclear structure, nuclear astrophysics, and for nuclear reactor applications.

For neutron-rich nuclei far from stability, $\beta$-delayed neutron emission becomes the dominant decay process. The neutron emission probability ($P_n$ value) helps to verify the modeled $\beta$-strength distribution and the level structure of the daughter nucleus. Also the $\beta$-decay half-life of the parent nucleus can be determined via $\beta$-delayed neutron emission.

 Explosive astrophysical scenarios in neutron-rich environments like the “rapid neutron-capture” (r) process are responsible for the creation of about half of the stable isotopes beyond iron. In core collapse supernova explosions or the merging of neutron stars with a neutron star or a Black Hole, neutron densities in excess of $\gg 10^{20}$ cm$^{-3}$ can be reached, and ignite the r-process nucleosynthesis for a few seconds. Fast subsequent neutron captures and $\beta$-decays create very neutron-rich, heavy isotopes, most of which have not yet been discovered. When the temperature and neutron density drop rapidly due to the rapid expansion of the r-process rich material, the so-called “freeze-out” allows the neutron-rich material to decay back to stability via long $\beta$-decay chains.

$\beta n$-emitters in these decay chains can influence the neutron budget in the late-time evolution of the r-process in two ways: the emission of neutrons leads to a transfer of material into $\beta$-decay chains with lower mass number, and the emitted neutron can be thermalized and recaptured by the decaying material. Thus an accurate knowledge of the neutron-branching ratio and half-lives of as many $\beta n$-emitters as possible is a crucial prerequisite for improving theoretical models to achieve a better understanding of r-process nucleosynthesis models.

In fission reactors the longer response time of $\beta n$ allows keeping the system in a controlled subcritical state. Although their number (delayed neutrons per fission event) is only in the order of 1% of the total neutron yield, they have a long enough effective lifetime to insert or withdraw rods containing neutron absorbing materials to control the reactor.

Out of the 2,451 isotopes listed in the latest Atomic Mass Evaluation (AME2016) [1], 621 are $\beta$-delayed neutron emitters. However, for only 298 of them (48%) a measurement of the one-neutron branching ratio ($P_{1n}$ value) exists (Figure 1). For $\beta$-delayed multiple-neutron emitters, this ratio drops to less than 8%, and so far only one $\beta$-delayed four-neutron emitter ($\beta 4n$) has been measured, $^{17}$B.

There are two main reasons for the low number of measurements:

- The communities were so far focused on “easy” to reach nuclei, thus light nuclei with $A < 30$, and fission fragments around $A = 90$ and $A = 135$.
- The production rate for more neutron-rich isotopes at current radioactive beam facilities falls approximately by one order of magnitude per mass unit.

Setups using moderated proportional neutron counters, such as $^3$He- or BF$_3$-filled tubes, are the most efficient way to detect $\beta$-delayed neutrons. Previous setups have reached (one-) neutron detection efficiencies of up to 60% (see Figure 2). To further increase the

![Figure 1. Number of identified $\beta n$-emitters with $Q_{\beta n} > 0$ keV (within the uncertainties, from AME2016) and number of isotopes where the neutron-branching ratio has been measured (Status: June 2016, isomeric states not included).]
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detection efficiency despite the drastically increased prize for $^3$He, the merging of tubes from existing neutron detectors is the most cost-effective solution.

The BRIKEN project was initiated in 2012, after the successful campaigns of the BELEN collaboration at GSI Darmstadt, Germany [2] with the BELEN-30 detector, and at the IGISOL facility in Jyväskylä, Finland with the BELEN-20 and BELEN-48 detectors [3–5]. For the detection of ion and beta particles the state-of-the-art “Advanced Implantation Detection Array” (AIDA) was used, which was developed by the University of Edinburgh, University of Liverpool, STFC Daresbury Laboratory, and STFC Rutherford Appleton Laboratory [6, 7].

The “Beta-delayed neutrons at RIKEN” project was born with the goal to design the world’s most efficient neutron detector array and set it up at the presently most powerful facility to produce neutron-rich isotopes. By 2013 the size of the collaboration had doubled, and the setup with the originally 52 $^3$He tubes provided by UPC Barcelona, IFIC Valencia, and GSI Darmstadt (from the BELEN detector), had almost quadrupled to up to 179 available $^3$He tubes. The additional tubes were provided by Oak Ridge National Laboratory (81 counters from $^3$Hen) [8, 9], JINR Dubna (20 counters from VASSILISSA) [10], and RIKEN (26 counters). In addition, $\gamma$-ray detection capabilities were implemented by the addition of two large-volume HPGe clover detectors from Oak Ridge National Laboratory. Between 2013 and 2016 an extensive conceptual design study was carried out for two versions of the BRIKEN array: a “hybrid mode” including the two clover detectors (BRIKEN-148H) and a high-efficiency “compact mode” (BRIKEN-148C and BRIKEN-166C) [11]. The hybrid setup can be easily transformed into a compact design with 166 counters, which increases the average detection efficiency for single neutrons up to 1 MeV from 68.6% to 75.7% (BRIKEN-166C).

For very neutron-rich nuclei with a large $\beta n$-energy window, a strong dependence of the detector efficiency on the neutron energy might hamper the respective measurement of the neutron branching ratios. Thus special care was taken in these simulations to design a neutron detector that has a relatively constant and high neutron detection efficiency up to 1 MeV with small variations up to 5 MeV (Figures 2 and 3).

A comparison of the design efficiencies for the hybrid and compact versions of the BRIKEN array and other existing neutron detectors for $\beta$-delayed neutron experiments is shown in Figure 2.

The presently most powerful facility for the production of neutron-rich isotopes is located at RIKEN Nishina Center in Wako, Japan. At the “Radioactive Ion Beam Factory” (RIBF) a $^{238}$U beam with 345 MeV per nucleon is impinging on a production target, and the neutron-rich fragments are filtered out by the BigRIPS fragment separator and the Zero-Degree Spectrometer, and are then stopped in the stack of six double-sided silicon-strip detectors (DSSDs, wafer size $8 \times 8$ cm$^2$) in the implantation detector AIDA, which serves as an ion and beta counter. AIDA is surrounded by the respective BRIKEN neutron/gamma detector array.

The BRIKEN project relies fully on digital electronics systems. The GASIFIC triggerless DAQ—developed by IFIC Valencia for the BELEN detector [5]—has been upgraded, and a set of software tools for data analysis have been developed.
The setup has been installed and commissioned in 2016. For the first phase of the BRIKEN campaign in 2016/17 the hybrid setup with 140 counters and two clovers was used, with a detection efficiency that closely resembles the one given for BRIKEN-148H in Figure 2.

Two experimental proposals have very successfully been carried out in the first campaign, focusing on βn-emitters around and beyond the shell closures at N = 50 and N = 82. In addition, the preparatory phase of another proposal aiming the measurement of β-decay properties at the N = 104 mid-shell closure was completed.

The first experiment produced and implanted a world record number of 7,500 doubly magic $^{78}$Ni nuclei (Z = 28, N = 50), about three orders of magnitude more than in a previous experiment at NSCL [12]. In the region between $^{75}$Co and $^{96}$Br in total about 30 β1n- or β2n-branching ratios were measured, many of them for the first time, as well as 20 β-decay half-lives.

The second experiment focused on the region around the N = 82 shell closure, which is of particular interest for astrophysics. The solar abundance curve shows an abundance peak at A ≈ 130, which is directly connected to neutron-rich βn-emitters at N = 82 produced by the r-process. About 30 new neutron-branching ratios were measured in a region at or very close to the r-process path predicted by some astrophysical models, including some of the heaviest β-delayed multiple neutron emitter.

The third experiment is focused on deformed βn-emitters, which are critical for understanding the formation of the rare-earth abundance peak at A = 160 during the r-process. Presently there is a large gap between $^{150}$La (Z = 57) and $^{210}$Hg (Z = 80) with no measured neutron-branching ratios. The preparatory phase of this experiment was completed in June 2017 by verifying the production cross-sections. Although only a small fraction of this experimental program was carried out, already 10 P1n values and β-decay half-lives were measured for the first time.

The BRIKEN collaboration (Figure 5) has carried out the second phase of measurements in fall 2017. The previous statistics for the A = 80 region could be tripled, and many new beta-delayed neutron emitters in the A = 100–125 region could be added. For this phase, an adaption of the hybrid setup was used to increase the gamma-detection efficiency of the
two clover detectors. In the first phase each clover was 68 mm away from the implantation area. In the new design this distance was reduced to 38 mm, which allowed doubling the efficiency and reaching a value that is roughly half of that of the EURICA array.

After these successful first experiments, the BRIKEN collaboration is planning to continue their measurements until at least 2019. With this setup, the largest investigation of $\beta$-delayed neutron emitters so far is being carried out, measuring well over a hundred $\beta_{1n}$-, $\beta_{2n}$-, and $\beta_{3n}$-emitters, and in the future also $\beta_{4n}$-emitters, in the mass region between $A = 10$ and 210, many of them for the first time. This effort will help to better understand $\beta$-delayed neutron emission, the dominant decay mechanism of neutron-rich nuclei.

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**References**

The third international conference on Advances in Radioactive Isotope Science, ARIS 2017, was held for the first time in North America at the Keystone Conference Center in Keystone, Colorado, USA, from Sunday, 28 May through Friday, 3 June 2017. The meeting was jointly organized by NSCL/FRIB (Michigan State University, USA) and TRIUMF (Canada). ARIS is the flagship conference series for rare-isotope science that resulted from a merger a few years ago of the “International Conference on Exotic Nuclei and Atomic Masses (ENAM)” and the “International Conference on Radioactive Nuclear Beams (RNB).” Following the tradition of the ARIS meetings in 2011 (Leuven, Belgium) and 2014 (Tokyo, Japan), ARIS 2017 facilitated a vibrant and extensive information exchange. More than 277 scientists from 23 countries attended “ARIS in the mountains,” as the meeting was dubbed due to its location in the Rockies at a high base elevation of 9,280 feet or 2,830 meters (Figure 1).

The conference opened with a plenary session on precision measurements and fundamental symmetries, followed by plenary sessions on nuclear astrophysics, and on the intersection of nuclear structure and reactions. The first day then ended with a special plenary session with new results hot off the press that was organized short-term to accommodate some of the most recent work in the field. The second day was kicked off by two plenary sessions on the study of the heaviest elements and nuclear structure insights from spectroscopy, respectively. The afternoon was devoted to shorter talks that were presented in two parallel sessions. In the evening, more than 120 posters were intensely discussed during the dedicated poster session that only ended late in the evening when the conference center staff left for the night. The posters of graduate students Andrew MacLean, Christina Burbadge (both from the University of Guelph, Canada), and Aaron Chester (Simon Fraser University, Canada) were awarded the European Physical Journal A Poster Prize. Wednesday had two plenary sessions in the morning, devoted to the nuclear theory frontier: from few to many-body systems, and fusion and fission studies, respectively. The afternoon was free for the attendees to enjoy the spectacular scenery around Keystone, on the mountain bike, while hiking, or during a ride on a historic railway. The day was closed with an evening lecture delivered by Graham Peaslee from Notre Dame University (Indiana, USA) who inspired attendees through a personal account of how to apply a nuclear science background to address environmental challenges. The program on Thursday started with plenary sessions on ground-state properties of nuclei and collective phenomena, continued with broad topics covered in two parallel sessions in the afternoon, and concluded with the conference banquet. The last day closed the meeting with three plenary sessions, on applied nuclear physics, nuclear masses, and with a special session on new developments and innovation. This last ses-

![Conference photo taken in front of the Keystone Conference Center and the spectacular mountain scenery of Colorado.](image-url)
sion also provided a speaking slot for the first-placed poster winner, Andrew MacLean, who presented his work on gamma-gamma angular correlations with the new GRIFFIN spectrometer.

Overall, results at the frontier of rare-isotope science were presented not only from all major facilities around the world but also unique work was underlined that is best performed at smaller laboratories. Essentially all sessions included presentations of experimental and theoretical research, showing the frontiers of both efforts at the same time and highlighting their close connection.

ARIS 2020 will take place in three years’ time in the south of France, hosted by the French nuclear physics laboratories of the CNRS, the CEA, the ILL, and in collaboration with GANIL.

ALEXANDRA GADE
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ADAM GARNSWORTHY
TRIUMF

EINN 2017

The conference on “Electromagnetic Interactions with Nucleons and Nuclei (EINN)” had been organized on Santorini and Milos Islands in Greece every other year since 1995. In 2011, its location was successfully moved to Paphos, Cyprus. The conference series covers experimental and theoretical topics in the areas of nuclear and hadronic physics. It also serves as a forum for contacts and discussions of current and future developments in the field. The conference has unofficially been a counterpart of the U.S. Gordon conference on photonuclear physics and held in alternate years with traditionally strong U.S. participation. No proceedings are produced, in the tradition of Gordon and Euroconferences, in order to encourage the frank exchange of even tentative information.

The 12th EINN conference took place in Paphos, Cyprus from 29 October to 4 November 2017 and attracted 84 participants from 39 institutes located in 15 countries in Europe, North America, Asia, and Australia. The conference was dedicated to the memory of Dr. Kees de Jager, the first conference chair in 1995, who passed away in 2016.

Since 2011, the conference program has organized dedicated sessions for postdoctoral fellows and advanced graduate students, who receive financial support. This year the conference again added a two-day, pre-conference event on Frontiers and Careers in Photonuclear Physics—skill development and talks for students, which was very well-received by the students. More than 35 students and postdoctoral fellows participated in the conference by receiving partial support. A highlight of the conference was the evening plenary poster session, which drew a large attendance with lively discussions that lasted over two hours. The authors of the three best posters, selected by secret vote of all attendees, from Hampton University, USA and Mainz University, Germany were awarded European Physical Society Poster Prizes, which comprised the Feynman Lecture Series and commemorative gifts (Figure 1). The three poster winners each presented a talk on the subject of their posters at the plenary section of the conference.

Social activities included: a welcome reception; an excursion to explore the fascinating history of Cyprus; a conference dinner that highlights the great hospitality of the island; and a farewell lunch, which provided the conference attendees with pleasant opportunities to engage in informal discussion.

The conference covered a wide range of theoretical and experimental developments in hadron physics, including: contributions beyond single-photon exchange, the proton radius puzzle, new experimental facilities, dark matter searches, neutrino physics, lattice QCD, spectroscopy, spin structure of the proton, precision electroweak physics, and new physics searches. With the study of QCD being a major focus of present activities and future plans in physics research worldwide, the EINN conference will continue to provide an important international forum, particularly for young physicists, for the foreseeable future.

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Figure 1. Presentation of European Physical Society Poster Prizes to the three winners: (left to right) EINN 2017 Chair Richard Milner, Oleksandr Tomalak, (U. Mainz), Cristina Collicott (U. Mainz) and Dongwi H. (Bishoy) Dongwi (Hampton U.).
Report on CGS16

The International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics (CGS) is a conference series started in 1969 in Studsvik, Sweden, and continued once every three years in Europe and North America. It was previously held in Petten, The Netherlands (1974); Brookhaven, NY, USA (1978); Grenoble, France (1981); Knoxville, TN, USA (1984); Leuven, Belgium (1987); Asilomar, CA, USA (1990); Fribourg, Switzerland (1993); Budapest, Hungary (1996); Santa Fe, NM, USA (1999); Prague, Czech Republic (2002); South Bend, IN, USA (2005); Cologne, Germany (2008); Guelph, Canada (2011); and Dresden, Germany (2014). The CGS conferences initially focused on topics related to gamma-ray spectroscopy, but later extended the scope to include nuclear astrophysics and interdisciplinary studies. It is one of the largest series of meetings in nuclear physics.

For the first time in its history of nearly half a century, the CGS meeting in 2017 moved to Asia. In the pleasant early-autumn season, the sixteenth of this series (CGS16) took place in Shanghai, China, from 18–22 September 2017. It was held in the quiet historical campus of Shanghai Jiao Tong University located in the heart of the metropolis Shanghai (Figure 1). Shanghai Jiao Tong University, as one of the higher education institutions that enjoys a long history and is becoming a comprehensive, research-oriented, and internationalized top university in China, was proud to host this world-class conference.

The CGS16 attracted nearly 200 participants from 22 countries (Figure 2). In the five-day scientific program, a total of 128 talks were presented in 32 sessions. The talks were devoted to Nuclear Structure, Nuclear Reaction, Nuclear Astrophysics, Challenges in Nuclear Theory, Fundamental Symmetries, Novel Experimental Techniques and Facilities, and Interdisciplinary Studies and Applications. The contributed talks were selected from well-established researchers as well as the younger generation. Female nuclear physicists played noticeable roles in CGS16; about one quarter of the invited speakers and one quarter of the session chairs were women.

At the end of CGS16, the international advisory committee made the decision that the next CGS symposium, CGS17, will take place in 2020 in Grenoble, France.

YANG SUN
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The Electron-Ion Collider (EIC) is a proposed facility to be built in the United States to study hadron physics using polarized electrons colliding either on polarized light ions or unpolarized heavy ions at high luminosity and with the possibility to change the center of mass energy between 20 and 100 GeV or more. The EIC has been recommended by the Nuclear Science Advisory Committee of the U.S. Department of Energy (DOE) within the 2015 Long Range Plane for Nuclear Science. At present, the project is undergoing the review of the U.S. National Academy of Science (NAS) and the outcome is expected within a few months. The physics case [1] is focused around key issues in hadron physics. In spite of important recent progress, with key contributions from Europe-based and U.S.-based experiments (COMPASS at CERN SPS, HERMES at DESY HERA, experiments at JLab), the study of the spin dependent and spin independent multidimensional structure of the nucleon in its nonperturbative regime need the precision that can be reached only by the luminosity provided by the EIC coupled to a modern and hermetic experimental setup. In the heavy nucleus sector, where intense research is performed by ALICE at CERN LHC, fix target experiments at CERN SPS and at the RHIC collider at BNL, the nucleus investigation by the electron probe, a powerful QCD laboratory, will offer novel opportunities to answer urgent open questions such as QCD behavior at extreme parton densities, nucleus tomography, propagation of a color charge in QCD matter, and the distribution of quarks and gluons in nuclei. Moreover, the high luminosity available by EIC and the polarization options also offer a unique opportunity to test fundamental symmetries, a way toward signals of physics beyond the standard model.

A large community of EIC future users and supporters, presently formed by more than 700 scientists from the United States and from all over the world, with about 25% of the members from Europe, is emerging and grouped in the EIC User Group (EICUG), which promotes the realization of the EIC and its science. In the past, this community has met in the United States (at Stony Brook in June 2015, at Berkley in January 2016, at Argonne in July 2016), while the 2017 meeting (EICUG2017) took place in July in Trieste, Italy, hosted by the Istituto Nazionale di Fisica Nucleare (INFN), with the local support of the INFN Sezione di Trieste and the University of Trieste. Several motivations have suggested holding the meeting in Europe. In fact, on top of the usual scientific progress represented by all the EICUG meetings, EICUG2017 has offered an opportunity to the entire European nuclear physics community to learn more about EIC, and it has allowed the interested European physicists to get together in an appropriate context: a unique opportunity in view of the formation of a coherent collaboration.

One-hundred and twelve scientists have attended the meeting (Figure 1). The largest national representatives are from the United States, Italy, and France, with remarkable participation of physicists from several other Europeans and non-Europeans countries (Algeria, Australia, Belgium, Cyprus, Czech Republic, Finland, Germany, Japan, Netherlands, Spain, Switzerland, and the United Kingdom). The scientific program, dedicated to the EIC scientific case and to the corresponding detector requirements, includes 25 plenary invited talks and 50 talks presented in the parallel sessions. The meeting was preceded by a one-day workshop dedicated to the accelerator aspects of the EIC project and it has created an opportunity to let accelerator scientists from the United States and Europe meet together in a constructive and friendly atmosphere.

Important statements have been given by the representatives of ma-

Figure 1. The participants of EICUG2017.
Major scientific institutions during the EICUG2017 opening session. Tim Hallman, Associate Director of Science for Nuclear Physics at DOE, in presenting the DOE Nuclear Physics perspective on a possible future EIC, has offered a very positive view indicating that the plans for an EIC should continue to be vigorously pursued in anticipation of the outcome of the NAS review and the next steps that may lead to. He has also expressed support for the internationalization of the project. Angela Bracco, chairperson of the Nuclear Physics European Collaboration Committee (NuPECC), presented the 2017 NuPECC Long-Range Plan and its connection to EIC: the science at EIC is highly recognized by NuPECC, as well as the importance of international collaborations outside the European boundaries; in fact, it is well known that European groups will bring their very valuable expertise in technical and scientific issues; several members of the hadron physics and heavy ions communities in Europe are potential users in the future EIC. Barbara Erazmus, coordinator of the European Integrated Initiative in Hadron Physics, expressed strong interest in EIC welcoming EIC-related projects in the Initiative. Patrice Verdier, Associate Director of Science for the particle and hadron sector of the French CNRS National Institute for Nuclear and Particle Physics (IN2P3), discussed the IN2P3 visions and plans presenting the outstanding resources and expertise of the Institute and expressing strong scientific interest for EIC physics. Anne-Isabelle Etiennevre, director of the Institut de recherche sur les lois fondamentales de l’Univers (IRFU) at the Commissariat à l’Energie Atomique (CEA), presented the IRFU visions and plans for nuclear and particle physics, illustrating their impressive infrastructure resources and stating their strong interest in long-term hadronic physics contributions with technical developments from CEA including instrumentation, data analysis, and phenomenology. Eugenio Nappi of the Italian INFN Executive Board discussed the INFN vision and plans for nuclear and particle physics and illustrated the outstanding INFN technical resources and infrastructure. He stated that, within INFN, there is a potential community of more than 110 experimental physicists interested in EIC, some of them already contributing to the EIC physics case and to the Generic Detector R&D for an Electron Ion Collider. INFN considers EIC an important opportunity for the hadronic physics community and encourages partnerships and collaborations with the other institutions involved in the project.

In summary, EICUG2017 in Trieste has contributed to form the basis for the future engagement of the interested European hadron community in the EIC project, matching two main goals: increasing the interest for the EIC project within the community of the European nuclear physicists, at various levels (individual scientists, scientific teams, and major institutions) and opening the way to effective collaborations toward the experimental activity at EIC among European physicists and between them and colleagues in the United States.

References
2. eicug2017.ts.infn.it/

Michael Thoennessen Selected as APS Editor-in-Chief

Michael Thoennessen was recently appointed as the new Editor-in-Chief of the American Physical Society and took office on 1 September 2017. As such he will be in charge of all editorial issues of the APS journals, including the Phys. Rev. series, Phys. Rev. Letters, and Rev. Mod. Phys. and will manage the editorial work based at the Ridge, NY offices.

Michael has had a long and distinguished research career, and high international stature in Nuclear Physics, physics education, mentoring, and management activities and he takes over with a broad and deep knowledge of the field.

Following a Diplom degree in Cologne in 1985, a Ph.D. from the University of New York at Stony Brook in 1988 (on giant resonance in atomic nuclei), and a Post-doc at Oak Ridge National Laboratory, he came to Michigan State University (MSU) in 1990, rising to full professor in 1998, and University Distinguished Professor in 2015. At the MSU Cyclotron lab, he has been the Associate Director for Nuclear Science, and for Education, and Associate Lab Director for User
relations. Thoennessen’s research has been wide ranging, with foci on exotic nuclei and on instrumentation and reactions involving neutron ejectiles, on neutron unbound states, neutron radioactivity, and the low lying states of exotic light neutron-rich nuclei. His long-standing and productive research career comprises over 220 papers and over 160 Invited Talks worldwide.

He was selected as a Fellow of the American Physical Society (APS) in 2005 and as a Physical Review Outstanding Referee in 2013. He won the Division of Nuclear Physics (DNP) Mentoring Award in 2012, and was elected Chair of the DNP for 2017. Finally, he served as a Supervisory Editor for Nuclear Physics for more than a decade (2004–2016).

He comes to his new position with a strong history of outreach activities on behalf of education, gender diversity, and the nuclear physics community. He recently published a well-received history of the discovery of every single isotope. He has been a member of the U.S. DOE/NSF Nuclear Science Advisory Committee and has served on numerous APS, DNP, and national and international committees, including stints as Chair of the DNP Education Committee (2014–2015), the APS Education, and Gender Equity Committees.

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A New FET Collaborative Project: Testing the Large-Scale Limit of Quantum Mechanics—TEQ

Quantum physics is the bedrock of all modern science, going from chemistry and biology, to optics and nuclear physics.

There is no doubt that quantum mechanics works with incredible accuracy: we can calculate with extreme precision processes in nuclear physics, such as nuclear decays, reactions, and interaction rates. In spite of its powerful capacity to perform accurate predictions, why quantum mechanics works, its interpretation, and possible limits are far to be fully understood. In this context, one of the most intriguing issues is the superposition principle inherent to quantum mechanics, namely the fact that in quantum mechanics we find superpositions of all possible states and only when a measurement is performed does the state collapse to its unambiguous outcome.

In standard quantum mechanics this is realized by the collapse of the wave function postulate, which triggered many discussions in the last 100 years, which are still alive.

Whether we can observe quantum superpositions (QSP) of macroscopic objects is arguably “the” open question in quantum physics. An answer in the positive direction will boost the quest for the use of the weirdness of quantum mechanics in a much larger set of physical systems, not restricted to the microscopic world.

Recently, a team of scientists have joined in a consortium to address this fundamental quest from an innovative standpoint, supported by a FET € 4.4M grant awarded by the European Commission. The Collaborative Project “TEQ” (Testing the large-scale limit of quantum mechanics) puts together eight leading European research groups: University of Trieste (PI)—Italy; Aarhus Universitet—Denmark; Istituto Nazionale di Fisica Nucleare—Italy; Oesterreischische Akademie Der Wissenschaften—Austria; The Queen’s University Belfast—United Kingdom; Technische Universiteit Delft—The Netherlands; University College London—United Kingdom; University of Southampton—United Kingdom; and the MSquared company from the United Kingdom to explore quantum effects at the large scale under the support of the EC Horizon2020 research framework program. The project is one of only 26 funded proposals out of 374 submitted to the latest call for Future and Emerging Technologies projects.

The team will levitate a small particle within a well-controlled environment, with low temperature and low vibrations. In such an environment an indirect test of the QSP can be performed by analyzing carefully the noise that affects the center of mass motion of the trapped particle. The measured noise will then be compared to the theoretical predictions from different models—some of which assume a breakdown of QSP.

The ambition of the project is to establish the ultimate bounds to the validity of the quantum framework, if any. Within TEQ, a big step forward, both in fundamental science and for the future quantum technologies, from ground to space, could be achieved.

The project will start in January 2018 and will last four years. For more information on the TEQ Consortium and project visit www.tequantum.eu

CATALINA CURCEANU
LNF-INFN

ANGELO BASSI
University and INFN Trieste, Italy
IUPAP Meetings and Nuclear Science Symposium at Nihon-Bashi

The IUPAP Commission 12 (for nuclear physics) and Working Group 9 (WG.9: on international cooperation in nuclear physics) meet annually, usually on consecutive days. The most recent meetings were held at the RIKEN Tokyo office in Nihon-Bashi, Tokyo, 29–30 August 2017. Nihon-Bashi means Japan-Bridge, which looked like Figure 1 in the Edo era, and the 113th element nihonium is named after Nihon (Japan, or Nippon). It is clear from the name of the place that the office is in a very posh central district of Tokyo and in the same building as Bank of America Merrill Lynch.

Every two years the meetings are organized together with the Nuclear Science Symposium (NSS) in which recent progress in nuclear physics and related developments are reviewed and discussed as seen in Figure 2 in the presence of invited representatives from the national funding agencies from around the world. This time 14 such representatives participated in the symposium from NRF (Zuid-Afrika), NSERC/NRC (Canada), CNRS/IN2P3 (France), INFN (Italy), ANSTO (Australia), the Department of Energy (USA), STFC (United Kingdom), RIKEN (Japan), CEA (France), and the Chinese Academy of Sciences (China), as lining up in Figure 3.

During the symposium, special in-camera meetings for the funding agency representatives were held. These meetings are meant to learn about the progress in nuclear science, and exchange the status in their countries, and to see how their efforts fit into an international framework. The agenda and slides from the symposium can be found at http://triumf.info/hosted/iupap/icnp/nss2017.html.

Shoji Nagamiya, who chaired the in-camera meetings, made a briefing at the end of the IUPAP WG.9 annual general meeting as follows:

1. The participants of the in-camera meetings recognized that an unprecedented era of nuclear science will be realized, especially by the next generation of Rare Isotope Beam Facilities around the world.
2. They showed concerns about the questions that have arisen on the open access policies to the large nuclear science laboratories and the question of user fees.
3. They recommended that IUPAP WG.9 may take a more explicit role on international cooperation for the large scale nuclear science projects.
4. They recommend IUPAP WG.9 to consider positively as “international” a project where the share of responsibilities is discussed in IUPAP WG.9 from the beginning of the project by including all the stake holder countries.
5. They also stressed the importance of small-scale university-based nuclear science laboratories because these are essential training grounds for young scientists.

Similar discussions were also made at the IUPAP WG.9 annual general meeting. Shigeo Koyasu, executive director of RIKEN, described the future plans for operations of the Rare Isotope Beam Facility at RIKEN. He suggested the possibility of asking the users to bear the cost (collaboration fee), not for the electricity, but for miscellaneous expenses for the common fund for experiments.
There was a wide-ranging discussion of such user fees in the meeting. A general concern is that if one facility implements such charges, other facilities would then be forced by their funding agencies to follow suit. This could have serious consequences on the scientific productivity and mobility of the international community. Some opinions generally supported by the members were: (1) Beam time should be granted based on scientific excellence. Any payments for beam time goes against this general principle. (2) There is an established tradition for the user community to share some of the operating costs, but it is not connected to beam hours. (3) The host institute must be very clear about what these user fees can cover. The funding agencies may refuse to allow the use of grant funds to pay these, which might cut off a facility’s access to international, talented research scientists.

Other issues discussed in IUPAP WG.9 include: a report from the Asian Nuclear Physics Association (ANPhA) by Kazuhiro Tanaka; a report from the US Nuclear Science Advisory Committee (NSAC), by David Hertzog; the Five Year Plan for TRIUMF in Canada, by Jonathan Bagger; a report from the Nuclear Physics European Collaboration Committee (NuPECC) by Angela Bracco; Nuclear Science in Latin America, by Alinka Lepine-Szily; and the i’Themba Labs and the South-African Isotope Facility, by Faical Azaiez. IUPAP WG.9 also decided to update the laboratory descriptions around the world in IUPAP Report 41 (http://www.triumf.info/hosted/iupap/icnp/report41.html).

The next meeting of IUPAP WG.9 will be held in Italy (venue and dates are under discussion).

**HiDeTo En’yo**

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2018

April 17–20
Groningen, The Netherlands. ENSAR2 Town Meeting
http://www.ensarfp7.eu/

April 20–22
Antalya, Turkey. 4th International Conference on Theoretical and Experimental Studies in Nuclear Applications and Technology (TESNAT 2018)
https://2018.tesnat.org/

May 13–18
Galveston, Texas, USA. 4th International Workshop on “State of the Art in Nuclear Cluster Physics” - SOTANCP4
https://cyclotron.tamu.edu/sotancp4/

May 13–18
Marianske Lazne, Czech Republic. RadChem 2018 – 18th Radiochemical Conference
http://www.radchem.cz/

May 22–25
Catania, Italy. IWM-EC 2018 International Workshop on Multi facets of Equation of state and Clustering
http://www.ct.infn.it/iwm-ec2018

May 22–25
Longyearbyen, Spitsbergen, Norway. 14th Nordic Meeting on Nuclear Physics
http://www.mn.uio.no/fysikk/english/research/news-and-events/events/conferences/14th-nordic-meeting-on-nuclear-physics/

May 22–25
Padova, Italy. 9th International workshop on Quantum Phase Transitions in Nuclei and Many-Body Systems
https://agenda.infn.it/conferenceDisplay.py?confId=13348

May 27–June 1
Giens, France. EURORIB 2018 - European Radioactive Ion Beam Conference
https://eurorib2018.sciencesconf.org/

June 4–8
Matsue, Japan. 10th International Conference on Direct Reactions with Exotic Beams (DREB) 2018
http://indicoids.riken.jp/indico/conferenceDisplay.py?confId=2536

June 7–12
Kraków, Poland. MESON2018 15th International Workshop on Meson Physics
http://meson.if.uj.edu.pl/

June 11–14
Ann Arbor, MI, USA. SORMA 2018
http://rma-symposium.engin.umich.edu/

June 11–15
Aachen, Germany. 7th International Symposium on Symmetries in Subatomic Physics (SSP 2018)
https://indicoids.cern.ch/event/651952/

June 18–22
Ohrid, Macedonia. Sixth International Conference on Radiation and Applications in Various Fields of Research (RAD 2018)
http://www.rad-conference.org/

June 24–29
Brasov, Romania. Nuclear Photonics 2018
http://nuclearphotonics2018.eli-np.ro

July 1–6
Caen, France. SHIM - ICACS 2018
http://www.shim-icacs2018.org/

July 9–13
Caen, France. FB22 - XXII International Conference on Few-Body Problems in Physics
https://fb22-caen.sciencesconf.org/

July 9–14
Toulouse, France. ESOF2018
https://www.esof.eu/en/

July 23–25
Osaka, Japan. International Conference on Atomic & Nuclear Physics

August 5–10
East Lansing, MI, USA. Nuclear Structure 2018
https://indicoids.fnal.gov/conferenceDisplay.py?confId=15187

August 11–17
Grapevine, TX, USA. CAARI 2018
http://www.caari.com/

August 26–September 2
Zakopane, Poland. Zakopane Conference on Nuclear Physics 2018 “Extremes of the Nuclear Landscape”
http://zakopane2018.ifj.edu.pl/

September 2–7
Bologna, Italy. EUNPC 2018
http://www.eunpc2018.infn.it/

September 10–15
Petrozavodsk, Russia. IX International Symposium on Exotic Nuclei, EXON-2018
http://exon2018.jinr.ru/

September 16–21
CERN Geneva, Switzerland. EMIS2018
https://indicoids.cern.ch/event/616127/

November 5–9
Gif-sur-Yvette, France. SSNET’18
https://indicoids.in2p3.fr/event/16782/

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