# Contents

**Editorial**  
Innovation and Integration for Clean Energy Production  
*by Luisa Cifarelli* ................................................................. 3

**Letter to the Editor**  
Should Publication in High-Level Scientific Journals be a Privilege of Large Laboratories?  
*by Rubens Lichtenthäler Filho* ...................................................... 4

**Laboratory Portrait**  
Microscopes for the Physics at the Femtoscale: GANIL-SPIRAL2  
*by Héloïse Goutte and Alahari Navin* ............................................. 5

**Feature Articles**  
The Thorium-Isomer: Heartbeat for a Nuclear Clock  
*by Peter G. Thirolf, B. Seiferle, and L. v. d. Wense* .................................................. 13

From Quarks to Nuclei: Short Range Correlations Studies Across the Globe  
*by Florian Hauenstein, Julian Kahlbow, and Or Hen* ......................... 19

**Facilities and Methods**  
Toward Machine Learning Optimization of Experimental Design  
*by Atılım Güneş Baydin, Kyle Cranmer, Pablo de Castro Manzano, Christophe Delaere, Denis Derkach, Julien Donini, Tommaso Dorigo, Andrea Giannanco, Jan Kieseler, Lukas Layer, Gilles Louppe, Fedor Ratnikov, Giles C. Strong, Mia Tosi, Andrey Ustyuzhanin, Pietro Vischia, and Hevjin Yarar* .................................................. 25

**Impact and Applications**  
How Theoretical Nuclear Physics Can Help Discover New Drugs  
*by Pietro Faccioli* ........................................................................ 29

**Meeting Reports**  
IPAC20, the First Virtual International Particle Accelerator Conference  
*by Mike Seidel, Ralph Altmann, and Frédéric Chautard* .................. 33

“Nucleodemic” Meeting NUCLEUS-2020  
*by Yu.N. Novikov and V. I. Zherebchevsky* ........................................ 34

Humanity and Physics Meet at Tenth Tastes of Nuclear Physics  
*by Nico Orce* ............................................................................. 35

**News and Views**  
JINR Long-Term Development Strategy  
*by Boris Sharkov* ....................................................................... 37

Jonathan Bagger Selected as CEO of the American Physical Society  
*by Benjamin F. Gibson and Rituparna Kanungo* ............................. 38

**Book Review**  
Review of *Pear-Shaped Nuclei* by Suresh Pancholi  
*by Joseph H. Hamilton* ............................................................... 39

**In Memoriam**  
In Memoriam: Hubert Grawe (1938–2020)  
*by Magda Górksa, Andrey Blazhev, Jürgen Gerl, Ernst Roeckl, and Dirk Rudolph* ............................................................... 40

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Cover Illustration: INDRA - FAZIA charged particle array at GANIL – see article on page 5.
In order to contribute to the training of young scientists working in the energy sector or intending to do so, the European (EPS) and the Italian (SIF) Physical Societies started the Joint EPS–SIF International School on Energy as a collaborative initiative. The courses are foreseen to take place on a biennial basis in the beautiful venue of Villa Monastero in Varenna, Lake Como, Italy.

The school was born during my mandate as EPS president (2011–2013) as a consequence of fruitful discussions with Friedrich Wagner, past EPS president and then chair of the EPS Energy Group. At the time, I was also SIF president, and this is why the venue of Villa Monastero was chosen. The villa had also previously hosted, in 2007, a meeting of the EPS Energy Group that was the preamble to the publication by SIF in 2008 of a white book concerning the Italian scenario: “Energy in Italy: Problems and Perspectives (1990–2020).”

The European energy supply situation is very inhomogeneous. There are countries that are nearly 100% CO\textsubscript{2}-free, and others with exclusively fossil-based electricity production. Some countries ban the future use of nuclear energy; for others, their dominant electricity production is based on it and they are building or planning new power reactors. Some export electricity to a large extent, while others have the need to import electricity. Some invest heavily in renewable energies (RE) and in other countries they do not yet play a major role. Despite this disparity, Europe has well-defined energy and environmental goals. In order to meet these goals, most European Union (EU) countries have to modify their energy supply technologies and have to increase their present renewable energy share. This requires extensive research and development in energy technologies and is a tremendous chance for students in all technical areas, but specifically in physics. Also, energy efficiency has to be increased clearly beyond the present measures taken in EU countries. The improvement of energy efficiency and the increase of energy intensity (which has been growing in the last decades) is a major challenge where again physics will play a key role.

The primary goal of the school is to present all physics fields with relevance for the technologies of energy production, conversion, transmission, and savings, thus addressing today’s most relevant energy issues. The potential of the various technologies has to be presented together with the need for continuous research and development to fully unfold them. This is why at the school a vast portfolio of basic lectures and topical seminars has to be foreseen by specialists in their field.

The unique feature of the school actually lies in its multidisciplinarity and interdisciplinarity, including basic and applied topics but also climate and economic aspects. Covering major fields in detailed lectures and bringing together scientists working in various energy related areas, the school is also meant to serve as a forum of discussion. This wide scope of the school is essential in order to provide the students (i.e., young scientists from all over the world), with a global insight into the complex nature of energy resources, supply, and consumption. The following fields are typically covered by lectures or seminars: solar photovoltaic, hydro, wind, biomass, fossils, fission, fusion, energy storage, energy-saving technology, environment and climate issues, along with other topics where physics plays a role.

The 1st Course was held in summer of 2012 on “New Strategies for Energy Generation, Conversion and Storage.” The 2nd Course, in 2014, was devoted to an overview of “Basic Concepts and Forefront Ideas on Energy,” covering the major scientific areas. The 3rd Course was, exceptionally, held in 2016 at the Ettore Majorana Foundation and Centre for Scientific Culture, in Erice, Italy, in collaboration with the Materials Research Society and EMRS, on “Materials for Energy and Sustainability.” The 4th Course was organized in 2017 back in Varenna, with the focus on “Advances in Basic Energy Issues.” In 2019, the 5th Course, titled “Energy: Where We Stand and Where We Go,” was successfully held and matched the primary goal of the school to present all research and development fields in energy matters. The 6th Course, foreseen for 2021, will target “Energy Innovation and Integration for a Clean Environment.”

For each of its courses the school gathered 50 to 60 participants—lecturers, observers, and students—of many different nations. The lectures were typically delivered by about 20 experts in various fields. The proceedings of the school, published as Lecture Notes, conserve the teaching material presented and make it available to those who did not attend the school. They serve as a reference book for both specialists working in one of the energy fields but with interests in the status of other energy-related areas, and nontechnical readers who...
want to get a general overview on the involved concepts and techniques and their prospects. These proceedings are published both on paper, in volumes of the Lecture Notes of the Joint EPS-SIF International School on Energy series, and on-line open-access in The European Physical Journal Web of Conferences.

We really hope that learned societies will continue to fulfill their mission, providing an appropriate and knowledgeable scientific input concerning the issue of clean and sustainable energy production. Despite the tremendous COVID times we are affording, this remains a challenge of paramount importance for our future generations.

Luisa Cifarelli
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Should Publication in High-Level Scientific Journals be a Privilege of Large Laboratories?

The purpose of this letter is to call attention to a topic that I consider to be of great importance. Lately, I have heard in conferences and in informal conversations with colleagues that publication of papers of experimental research made in small laboratories is going to become more and more difficult in high-level scientific journals. I understand that large laboratories invest a huge amount of money in updates of their experimental facilities and detection systems, aiming to respond to the most fundamental questions of nuclear physics and, in many cases, their experimental results are of high quality with small error bars. However, I believe that small laboratories and universities can also play an important role in the development of nuclear physics and should not be ruled out. Problems that have been overlooked by “big science” can be addressed in small laboratories providing significant contributions to the research area. Thus, I consider harmful any type of selection of papers based on criteria like that. Moreover, guidelines like that will probably condemn the small nuclear physics laboratories to death, in the long term. In my opinion statements, such as, “It will become more and more difficult to publish data from small laboratories or publication in high level scientific journals will be possible only for experiments performed in large laboratories,” should not be accepted passively or as a normal tendency. This kind of bias is not scientific and behind it there may be interests other than the purely scientific. I do not believe that editors and referees of important journals are intentionally implementing such policies. However, I do believe that there may be a subliminal bias in this direction expressed in informal conversations by important people in our area of research. In my opinion, guidelines like these are not beneficial to nuclear physics and will not improve the quality of publications.

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Microscopes for the Physics at the Femtoscale: GANIL-SPIRAL2

Caen, in Normandy, France, is famous as the home of William the Conqueror. Equally well known in the field of nuclear physics is the Grand Accélérateur National d’Ions Lourds (GANIL) laboratory and its major upgrade of the existing infrastructure, Système de Production d’Ions Radioactifs en Ligne de 2e génération (SPIRAL2) facility. GANIL is primarily focused on cutting edge research in fundamental nuclear physics using ion beams and is supplemented by strong programs in accelerator-based atomic physics, condensed matter physics, radiobiology, and industrial applications. For many decades, GANIL has provided High-intensity radioactive beams (12C to 238U), beams of short-lived nuclei (Radioactive Ion Beams), produced both by in-flight separation (lifetimes ~ μs) and isotope separation on-line (ISOL) technique (lifetimes ~ ms). The five-cyclotron complex delivers stable beams from energies ~1 MeV to 95 MeV per mass unit with currents up to 10 µA, fragmentation beams up to ~ 50 MeV/A, and reaccelerated beams (SPIRAL1) from 1.2 MeV/A to 25 MeV/A (~40 isotopes). The intensities of the radioactive beams range from a few particles/s to ~10⁷ p/s. The new superconducting linear accelerator (LINAC), in addition to very high-intensity light beams, also provides a fourth type of beam, namely neutrinos, to the already available arsenal of beams. These numerous types of beams are coupled to versatile detection facilities that allow the exploration of the behavior of nuclei in the phase space of excitation energy, angular momentum, and isospin. The first volume of Nuclear News (1991) portrayed the nuclear physics activities at GANIL, followed by the SPIRAL1 project (1995) and interdisciplinary physics (2000). In this article we present the evolution of the facility starting with the cyclotrons, the various associated detectors, and the current status of SPIRAL2. Figures 1 and 2 illustrate the cyclotron and LINAC complexes and their associated experimental halls. These complexes will be connected through a planned future project.

GANIL, a multibeam facility, has been delivering a wide spectrum of stable and radioactive ion beams since 1983. Between 1983 and 1990, the facility relied on a cascade of three warm cyclotrons (K_{CO} = 30, K_{CSS1} = 380, K_{CSS2} = 380). Subsequently, a second injector was added. Various techniques were developed to increase the beam intensities, the number of isotopes, and the reliability of these beams. A major upgrade, in 2001, was the availability of reaccelerated radioactive ions from the SPIRAL1 facility. The cyclotrons serve as the driver for the production of radioactive atoms in a thick carbon target that can be reaccelerated by the new Cyclotron pour Ions de Moyenne Énergie (CIME) (K = 265) up to a maximum energy of 25 MeV/u (the highest in the world today). A review of the work done using SPIRAL1 beams till 2010 can be found in Ref. [1]. An upgrade, started in 2014, for increasing the number of reaccelerated beams using a Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source coupled with a charge breeder, extends those available with the existing Electron Cyclotron Resonance (ECR) ion source. This, added to the already available secondary beams by using the in-flight method and stable beams, makes GANIL the only facility with this variety of beams. A continuous development of new and more intense stable beams, post-accelerated radioactive beams where GANIL has a niche, is ongoing. In parallel, there has been a continuous evolution in the detection systems, including the addition of various new detectors (discussed below). The functioning of the cyclotrons that has decreased in the last few years as a result of sharing the resources for construction of SPIRAL2, is being ramped up.

Ligne d’Ions Super Epluchés (LISE) Spectrometer

The LISE spectrometer [2] was one of the pioneering instruments to demonstrate the potential of studying nuclei very far from stability. (The use of double fragmentation was also pioneered at GANIL.) The initial use of LISE was to study atomic physics of high charge states using high-velocity ions. Nuclei are produced by fragmentation reactions on a thick target and selected by the doubly achromatic magnetic assembly. Later, a Wien filter and an additional beam-line, LISE2000, were also added. The design of the LISE spectrometer inspired the construction of fragment separator facilities in Asia, Europe, and the United States (the LISE++ simulation code is also widely used). A few of the pioneering highlights include the discovery of the existence of 48Ni, 100Sn, 2p-radioactivity, and the unbound nature of 28O. Recent improvements include the addition
of optical components to improve the focusing at the end of the spectrometer and the ongoing implementation of a new zero-degree detector to improve the particle identification. Charged particle detectors like MUr à STrip 2 (MUST2), γ-ray detectors, active targets, and so on are routinely used, in conjunction with the spectrometer, to study evolution of nuclear properties far from the valley of stability. Recent questions addressed include, in N=Z nuclei, proton–neutron pairing in $^{56}\text{Ni}$, $^{52}\text{Fe}$ using transfer reactions with MUST2 [3], and the signature of a possible alpha cluster state in $^{56}\text{Ni}$ using inelastic α scattering with the active target MAYA. Single particle structure in $^{17}\text{C}$, mirror symmetry in the unbound $^{12}\text{O}$ nucleus using transfer reactions, and proton radioactivity using ACtive TARget (ACTAR) were also carried out. Two proton correlations in $^{48}\text{Ni}$ and the nature of the $Z=6$ shell gap are some of the interesting problems that are currently being addressed.

Variable Mode Spectrometer (VAMOS++)

Unlike the LISE spectrometer, mainly designed for fragmentation energies, VAMOS was primarily designed for use with reaccelerated beams from SPIRAL1 and is also used with stable beams (especially in
inverse kinematics). This spectrometer is a large acceptance magnetic spectrometer, operating since 2001, which consists of three magnetic components: two large aperture quadrupoles followed by a dipole. The detection system of VAMOS, typically consisting of position sensitive multiwire proportional chambers and high-pressure ionization chambers, is used to measure the trajectory, velocity, energy, magnetic rigidity, and the $Z$ for the detected heavy ions. Detailed and extensive studies of the spectrometer and changes in its detection system allowed the maximization of the momentum acceptance (mean value $\Omega \sim 50$ mSr for $\Delta p/p \sim 0.3$) leading to its upgrade (viz., VAMOS++). Presently the resolution of atomic charge and mass are ($\Delta Z/Z \sim 1/70$) and ($\Delta A/A \sim 1/500$), respectively. A new fully digital readout system has also been implemented. VAMOS++ is used in a variety of experiments, coupled to detection systems like large gamma-ray arrays (Advanced Gamma Tracking Array [AGATA], Exotic Gamma-Ray Spectrometer [EXOGAM]), charged particle arrays (TIARA, MUST (MUr a STrip) Gaspard Trace [MUGAST], Identification des Noyaux et Détection à Résolution Accrues [INDRA]), and so on. VAMOS++, with its unique $A$, $Z$ resolution, has opened up new avenues to study the evolution of nuclear structure for nuclei far from stability, especially using isotopic chains of fission fragments [4] and products from deep inelastic scattering. It is also being used for studying fission dynamics [5] and new nuclei [6]. Ongoing improvements include the Particle-Identification Silicon-Telescope Array (PISTA) near the target and an improved identification of complementary fragment using a second detection arm. Investigations related to the structure of nuclei around the $N = 126$ shell closure, identification of new isotopes for heavy
Laboratory portrait

Figure 3. The major milestones in the increase in proton beam power.

nuclei, and studies of fission dynamics are underway.

INDRA–Forward Z&A Identification Array (FAZIA)

INDRA [7] is a charged particle array consisting of telescopes combining Si, CsI(Tl), and ionization chambers (564 detectors total), organized in 17 rings having a cylindrical symmetry around the beam axis and covering 90% of 4π. Reaction products can be identified for Z up to 92 with an isotopic resolution for A ≤ 8. FAZIA [8] was developed to have an isotopic resolution up to Z ~ 25, the granularity and signal processing capabilities. Using data from INDRA, the whole low-energy phase diagram of symmetric nuclear matter around the liquid–gas coexistence region has been mapped out, from multifragmentation to vaporization. In addition, many campaigns have greatly advanced the understanding of reaction dynamics in the Fermi energy range, where many-body correlations and fluctuations beyond a simple Mean Field description are essential to explain dissipative phenomena, in-medium effects, and fragment production. With the addition of FAZIA, the density dependence of the nuclear symmetry energy can be addressed through phenomena such as isospin transport. The measured velocity dependence of fragment neutron–proton ratios using FAZIA have been used to map out the degree of isospin equilibration in dissipative collisions around the Fermi energy, using INDRA to filter the relevant events. The density and temperature dependence for cluster emission from vaporization events will provide new information about in-medium effects in excited and dilute nuclear matter, as encountered in core-collapse supernovae environments.

MAYA–ACTAR

The low intensity of exotic beams poses an additional challenge for accessing the nuclear structure far from stability. In order to achieve reasonable reaction rates, one can increase the target thickness but with a deterioration in the reconstruction of the reactions kinematics. To overcome these effects, the active-target MAYA detector was developed at GANIL. MAYA is a 1-dimension Time and 2-dimension charge Projection Chamber (TPC) where the gas volume also plays the role of a target. Its segmented cathode allows the three-dimensional mapping of the trajectories and energy estimation of the ions produced in binary reactions within the active volume. These capabilities led to, for example, the discovery of the superheavy 7H resonance and of its structure [9] measurements of giant resonances in exotic nuclei and studies in inverse-kinematics for fission process. The search of unbound states and the measurement of excitation functions were possible as a wide range of energies could be scanned in a single experiment. Its upgrade, the ACTAR TPC detector, was designed within an international collaboration. Through a higher granularity in spatial and time dimensions, high particle-multiplicity detection, and dedicated digital electronics, ACTAR TPC [10] overcomes the limitations of MAYA. The nucleon–nucleon interaction is being probed at the limits, for example, with experiments on two-proton decay and in unbound systems. The equation of state is systematically studied with soft and giant resonances along isotopic chains. ACTAR TPC will continue its scientific program in the study of fission barriers, nuclear structure, and reactions with exotic systems, including using neutron beams at the Neutrons For Science (NFS) facility.

EXOGAM

Various γ-detector arrays used at GANIL range from the Château de cristal (74 BaF2 detector) and more recently the Photon Array for Studies with Radioactive Ions and Stable Beams (PARIS). The high-efficiency EXOGAM, developed for the SPIRAL1 facility, was the first spec-
AGATA

AGATA is the state of the art in Germanium technology, consisting of highly segmented HPGe crystals, with fully digital electronics, making use of the advanced technology of Pulse Shape Analysis and Tracking algorithms to achieve the best performance for a γ-detector array. AGATA (a European traveling detector), was commissioned in 2014 at GANIL and exploited along with the VAMOS++ [11] and will now move to Legnaro National Laboratory in Italy. The performances of AGATA allowed a very large gain in resolving power and thus opened new avenues in high-resolution discrete γ-ray spectroscopy at GANIL in addressing the evolution of shell structure [12], deformation, and cluster states in exotic nuclei. A campaign coupling AGATA and VAMOS++ with the MUGAST charged particle array, combined with reaccelerated Radioactive Ion beams (RIB) from the SPIRAL1 are presently addressing questions related to the α + 15O radiative capture rate, contribution of three body forces in nuclei, and so on.

Neutron Wall and Neutron Detector Array (NEDA)

The Neutron Wall consists of 50 tapered, hexagonal, closely packed liquid scintillators, covering ~1π at forward angles when placed at the nominal distance. Coupled with the EXOGAM array and a charged particle detector, a range of questions from neutron correlation in Borromean nuclei, to the evidence for a spin-aligned neutron–proton paired phase from the level structure of 92Pd [13] were addressed. The next generation NEDA has hexagonal detectors but not tapered. In the 2018 campaign, 54 (42) detectors of NEDA (Neutron Wall) [14] were coupled to AGATA and an improved DIAMANT detector. Compared to an earlier campaign with EXOGAM, the Neutron Wall electronics operated with analog electronics, whereas with the AGATA campaign the NUMEXO2 fully digital electronics were used for the neutron detectors. The main progress was the much-improved n-γ selectivity and the higher-detection efficiencies. As a result, for example, γ rays depopulating levels at a larger spin (up to a 14ℏ compared to 8ℏ) in 92Pd could be measured. The neutron arrays coupled to EXOGAM and the Global Reaction Array Si array are envisaged to explore dynamics and the structure of halo nuclei, shell evolution, and collectivity in regions far from the valley of stability.

Ligne d’Ions Radioactifs A Très basse énergie (LIRAT)

The LIRAT beam-line is used to transport radioactive ions (up to A ~ 85) with energies ≤30 keV delivered by the SPIRAL1 target-ion source. These low-energy ions are used to measure, among others, β-ν angular correlations, mirror β-decays, and branching ratio of 0+ to 0+ β-decays. The nuclear charge radius of 4He was also addressed using such low energy beams at the Séparateur d’Ions Radioactifs. The presence of a dark decay of neutron and tensor-type interactions in nuclear β-decay are among the topics being investigated.

Interdisciplinary Activities at GANIL

A wide choice of ions and energies gives access to the region at maximum energy deposition and thus allows a variation of the Linear Energy Transfer ranging from electronic to nuclear stopping powers. The very low end of this energy range at GANIL (<500 Kev) is provided by the Accélérateur pour la Recherche avec des Ions de Basse Energie. High-energy ions are used for studies on nano structuration of selective membranes and sensors developments based on topical 2-D materials (graphene, MoS2, etc.). Exploiting time/depth-resolved characterizations to their limit, the sensitivity of functional inorganic materials to dense electronic excitations is also studied. Other topics include understanding atomic diffusion during irradiation, related to lifetime of components used in radiactive environment and its study using coupled effects between electronic and nuclear energy losses. Defect engineering and predictions of radiation resistance in material science studies are also performed (e.g., hazardous evolution of polymers relevant to packaging of nuclear materials containing alpha emitters, geopolymer, and ion exchange resins). Measurements to understand the effect of irradiation on ageing and gas emission could be essential for the prediction of their long-term evolution and are also of interest. The role of cosmic rays and stellar wind on ices and silicates for the appearance of molecules in the universe is an open problem, in particular to understand the production and the radio-resistance of newly formed carbonaceous particles.
formed molecules during ice irradiation for understanding the emergence of life. Many experiments done here are devoted to the ion collisions-induced molecular complexification inside carbonated molecules clusters. These measurements, when compared to theoretical calculations, show the special role played by ion collisions in the molecular synthesis in space due to the specific interaction of heavy ions with matter. Avenues using new probes like electronic paramagnetic resonance spectroscopy are being investigated. Possibilities of studying colliding beams, or the possibility of \textit{in-situ} Rutherford Back Scattering (RBS) measurement and dual beam irradiation coupling “low” and “high” energy beams are also being examined. These activities are coordinated by the Center of Research on Ions Materials and Photonics at GANIL.

Irradiation and hardening of electronic components for space are performed using high-energy heavy ions. These studies include the Single Event Effect to improve the architectures and define testing standards used in space. Dedicated equipment for irradiation of polymeric films allows for industrial production with various ion tracks densities and ultimately very fine and uniform filters.

Double differential cross-section for charged particles with 95 MeV/A $^{12}$C beams on various elements that are relevant to hadron therapy is also investigated. At the Laboratoire de Radiobiologie avec des Ions Accélérés, various aspects related to the understanding of the biological effects related to direct and indirect (bystander) impact by carbon beams in cancer treatment are studied. The topics range from understanding differential cellular responses of radioresistant tumors to conventional radio and hadron therapy and explorations of the fundamental mechanisms of communication between irradiated and normal cells.

**Status SPIRAL2**

From the activities at the cyclotrons we now move to the new state-of-art LINAC and its experimental halls.

SPIRAL2 was approved in 2005, with the building construction starting in 2011. In 2006, along with the Facility for Antiproton and Ion Research in Germany, it was recognized as a European Strategy Forum on Research Infrastructures (ESFRI) facility and presently is a landmark ESFRI facility. The project was planned in two phases: the construction of a LINAC for very-high-intensity stable beams, and the associated experimental halls and the infrastructure for the re-acceleration (by CIME) of very intense short-lived fission fragments ($10^{13}$ ff/sec), produced using deuteron beams on a uranium target (the latter is currently on hold). SPIRAL2 is a result of strong French (Commissariat à l’Energie Atomique et aux énergies alternatives–Centre National de la Recherche Scientifique [CEA-CNRS]) and international collaborations. Its new superconducting LINAC and the NFS facility are now in a very advanced final stage of commissioning. SPIRAL2 will allow the exploration of the yet unknown properties of exotic nuclei near the limits of the periodic table of elements, by creating short-lived isotopes and measuring ground-state properties (such as the mass of the nuclei) with a high level of precision—a level equivalent to being able to measure a pea being added to the weight of an Airbus A380. The facility also provides beams of energetic neutrons that will open new avenues of research with both short- and long-term impact. It will help uncover yet unknown properties of the fission process, provide accurate and precise data necessary to better understand current and next-generation energy sources, delve into measurements necessary for more efficient production of isotopes for radioisotope therapy, and much more.

**LINAC**

Figure 2 shows the schematic layout of the LINAC accelerator along with its two existing experimental halls.

The LINAC at GANIL has been designed for different particles over a large range of ions, energies, and intensities (Table 1), unlike other large projects like LINAC4, Spallation Neutron Source (SNS), or European Spallation Source (ESS). This diversity of beams and energies required the design of a new compact multicryostat structure for the superconducting LINAC. At 200 kW in continuous-wave mode, the beam power is high enough to make a hole in the vacuum chamber in less than 35 µsecs! The operation of high beam intensities, like 5 mA, causes space-charge effects that need to be controlled to avoid a beam halo, which could activate components of the accelerator. The injector was successfully commissioned with 5 mA proton, 2 mA α particles, 0.8 mA oxygen, and 25 µA argon beams with transmission of 97% through the Radio-Frequency Quadruple (RFQ). In parallel, components of the LINAC were installed and cryomodules cooled.

**Table 1. Beam specifications.**

<table>
<thead>
<tr>
<th>Particles</th>
<th>H⁺</th>
<th>D⁺</th>
<th>Heavy ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/Q</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Max. I (mA)</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Min. energy (MeV/A)</td>
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<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Max. energy (MeV/A)</td>
<td>33</td>
<td>20</td>
<td>14.5</td>
</tr>
<tr>
<td>Max. beam power (kW)</td>
<td>165</td>
<td>200</td>
<td>45</td>
</tr>
</tbody>
</table>
NFS is 2 kW (40 MeV deuteron beam that the maximum power permitted at autumn 2021 at NFS. It should be noted used for PAC-approved experiments in sion. 40 MeV deuterium beams will be further characterize the beam transmis -
-ions. Additionally, thin targets (converters) of lithium/ beryllium was used to produce the first quasi-mono-energetic neutrons in September 2020. The energy spectrum and flux of neutrons produced at zero degrees were measured using a plastic scintillator. The neutron energies (1–30 MeV) were determined from the measured time flight of the neutrons between the production target and the detector with a suitable time structure of the proton beam. The quasi-mono-energetic spectrum of the neutrons produced by protons interacting with thin targets of lithium and beryllium is shown in Figure 5.

Continuous Neutron Spectra

A thick, rotating, beryllium converter (CEA, Irfu), designed for 2kW power dissipation, composed of an 8-mm-thick disk, rotating at 2,000 rpm was used to produce the continuous neutron energy spectrum. Power dissipation tests were performed, where the evolution of the temperature in different parts of the converter was measured as a function of the dissipated beam power. The measured temperatures agree with simulated values up to the maximum beam power of 1.35 kW used. The neutron energy spectrum measured by the time-of-flight method is shown in Figure 5. The measured spectrum is in good agreement with Ref. [16]. In November 2020, a first test experiment using a "white" neutron spectrum on two targets (CH₂ and C) was performed to measure the angular distribution of light charged particles using the (Si-Si-CsI) telescopes of the MEDLEY setup (University of Uppsala) with the NUMEXO2 digital readout system using electronic modules developed at GANIL. Figure 6 shows a typical 2-D plot of (ΔE₁–ΔE₂), the energy losses in the two detectors (ΔE₁–ΔE₂).

Next steps

The immediate steps at SPIRAL2 are to attain the design goal of full power allowed at NFS (2kW) with the deuteron beams for the start of the PAC-approved physics program in 2021. This year we also envisage having a simultaneous operation of both accelerators. Slightly longer term, work on the infrastructure is steadily proceeding on assembling the various available components of the Super Separator Spectrometer (S³) as they are being received. Simultaneously, work on the S³-Low Energy Branch (LEB) is progressing well. The start of commissioning of S³ is expected mid-2023. The Decay, Excitation, and Storage of Radioactive Ions experimental hall will be a bridge, receiving exotic beams both from S³ and SPIRAL1.
and is expected to start experiments in 2026. In parallel, a continuous improvement in the facility is planned, starting with the integration of a new A/Q = 7 injector to further sustainably increase the intensity of heavy ion beams at the LINAC. With the startup of this major upgrade at GANIL, plans for the next-generation facility and the future of GANIL are being studied by an international committee of experts. With its present state of the art facilities and their continuous evolution, GANIL–SPIRAL2 will allow us to explore the key questions related to, namely, understanding of how regular and simple patterns emerge in the intrinsic structure of complex many body nuclei and identify the degrees of freedom that govern the dynamics of their collisions. These explorations for understanding the physics of infinitely small systems under controlled conditions also have an impact on understanding the physics of infinitely large systems.

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The Thorium-Isomer: Heartbeat for a Nuclear Clock

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More than 6,000 years ago, Sumerians used light to measure time. They built sundials. Nowadays, laser light forms the basis of the most precise timekeepers: the most accurate time and frequency measurements are performed with optical atomic clocks, presently reaching an accuracy for the deviation of a time measurement by 1 second in about 33 billion years.

In general, a clock consists of an oscillator and a counting device for the frequency of the clock oscillation. Today's definition of the SI unit "second" uses a microwave transition in the element cesium, which is particularly suited, as it has only one natural isotope, $^{133}$Cs, and an atom beam can easily be produced due to the low evaporation temperature. About $10^5$ times higher frequencies are used in optical atomic clocks, still under development in the laboratory, while already reaching relative uncertainties of about $1 \times 10^{-18}$. In 2003, in order to further reduce these uncertainties, Peik and Tammm [1] proposed using a nuclear transition instead of an atomic shell state for time measurements. Due to the small nuclear moments (corresponding to the different dimensions of atoms and nuclei) and thus due to the very small coupling to external perturbing electromagnetic fields, a so-called nuclear clock promises an accordingly reduced vulnerability to external perturbations affecting the presently best optical atomic clocks. This enables a potentially more accurate operation of a nuclear clock.

In the concept of a nuclear clock [1, 2] (see Figure 1), a narrow-band laser will resonantly excite the nuclear clock transition, while the oscillations of the laser light will be counted using a frequency comb. After a certain number of oscillations, given by the frequency of the nuclear transition, one second has elapsed. This corresponds to the functional principle of optical atomic clocks, replacing their atomic shell transition by a nuclear transition.

The necessity of a direct laser excitation results in strong constraints to applicable nuclear clock transitions. Their energy has to be low enough to be accessible with existing laser technology, while simultaneously exhibiting a linewidth as narrow as possible. As the linewidth is determined by the lifetime of the excited nuclear state, the latter has to be long enough (i.e., an isomeric state) to allow for highly stable clock operation.

So far, only the first (isomeric) excited state of the actinide isotope $^{229}$Th qualifies as a promising candidate for a nuclear clock, due to its exceptionally low excitation energy allowing for direct laser excitation. The existence of this state was indirectly conjectured already in 1976 from $\gamma$ spectroscopic measurements to determine the nuclear structure of $^{229}$Th [3]. Since then, nuclear physicists have searched for direct decay signatures of this exotic nuclear state. By the current state of knowledge, the excitation energy of this "thorium isomer" $^{229m}$Th amounts to only $8.28 \pm 0.17$ eV (corresponding to a wavelength of 149.7 $\pm$ 3.1 nm) [4] and as such is the lowest nuclear excitation among all of the about 3,300 known nuclides with about 184,000 presently known excited nuclear states. Moreover, $^{229m}$Th exhibits a lifetime of a few $10^{-2}$ seconds, according to $\tau = h/\Delta E$, resulting in an extremely narrow relative linewidth $\Delta E/E \sim 10^{-20}$ for its ground-state transition. Besides the high resilience against external perturbations, this represents another attractive property in favor of constructing a Thorium nuclear clock that could rival today’s most advanced optical atomic clocks. Figure 2 im-

![Figure 1. Schematic operation of an optical nuclear clock. A cavity-stabilized frequency comb (generated by laser 1) will be adjusted to the nuclear excitation of $^{229}$Th. The excitation of the nuclear isomer will be detected by a continuous monitoring of the hyperfine splitting of an atomic shell transition (laser 2). This will change in case of a nuclear excitation due to the different nuclear spins of ground and excited states. When laser 2 is in resonance with the shell transition, photons will be detected at the photomultiplier tube (PMT) and laser 1 will be stabilized to the nuclear transition via a feedback loop. The frequency of the exciting mode of the frequency comb can very precisely be counted and serves as the clock signal. (Reprinted with permission from Physik-Journal (Wiley VCH, Germany), June 2020.)](image-url)
pressively illustrates the uniqueness of the thorium isomer in a display of the half-lives of all known nuclear isomers versus their excitation energies. 229m-Th resides far off all other isomers surrounded by typical atomic transitions being used in optical atomic clocks.

Realizing an optical control of the nuclear transition via a direct laser excitation would open a broad range of applications for a nuclear clock, from improved accuracy of satellite-based navigational systems or high sensitivity to minute fluctuations of the gravitational potential of the earth (e.g., induced by seismic or tectonic activities). The few-eV transition emerges from a fortunate near-degeneracy of the two lowest nuclear energy levels in 229Th. However, the Coulomb and strong-force contributions to these level energies differ on the MeV level. This would make the 229Th nuclear-level structure uniquely sensitive to variations of fundamental constants and ultralight dark matter [5].

In 2016, the first direct identification of the thorium isomer via the detection of its ground-state decay could be realized [6], bringing the long-term objective of the nuclear clock into the focus of international research in experiment and theory. Two different approaches have been proposed: one based on trapped ions and another one using doped solid-state crystals.

The first approach starts from individually trapped Th ions (e.g., in a Paul trap), comparable to trap-based optical atomic clocks. This approach promises an unprecedented suppression of systematic shifts of the clock frequency and leads to an expected clock inaccuracy of about $1 \times 10^{-19}$ [2], thus about an order of magnitude more accurate than the presently best optical atomic clocks. The other, radically different approach, relies on embedding of 229Th in vacuum-ultraviolet (VUV) transparent crystals (e.g., CaF$_2$) [1]. This bears the advantage of the large number (>10$^{15}$) of Th nuclei included in the crystal, leading to a considerably higher signal-to-noise ratio and a higher stability of the nuclear clock. However, a precise characterization of the thorium isomer’s properties remains a mandatory prerequisite for any kind of nuclear clock.

### Approaches to Determine the Excitation Energy

Presently, many groups worldwide work on characterizing the thorium isomer’s properties, targeting especially an improved determination of the excitation energy. Experimental approaches to determine the excitation energy fall into three categories: (1) indirect measurements via the γ spectroscopy of energetically low-lying rotational transitions in 229Th, (2) direct spectroscopy of fluorescence photons emitted in the decay of the thorium isomer, or (3) via the registration of electrons emitted in the internal conversion decay of 229mTh. These approaches will be discussed in the following.

1. Indirect energy measurements exploit higher-lying nuclear excitations of 229Th, which are populated in the α decay of 233U (see Figure 3) [7]. Some decay both into the nuclear ground state and the isomeric state, while emitting photons. The excitation energy of the isomer can be determined indirectly via the difference of these γ-ray energies. Such measurements were performed since the 1970s, first with germanium detectors, leading to an energy of $3.5\pm1$ eV in 1994 [8]. However, based on an improved measurement using a microcalorimeter, in 2007 the energy had to be raised to $7.6\pm0.5$ eV (and 2009 refined to $7.8\pm0.5$ eV) [7]. For more than a decade this value remained the best published value.

2. The second approach tries to measure the energy of photons directly emitted in the ground-state decay of the thorium isomer. Similar to the nuclear clock, two different scenarios also exist here: either thorium ions are stored in a Paul trap, or 229Th-doped crystals are used, whose band gap energy is large enough to be transparent for the expected (VUV) radiation. A mandatory prerequisite for a direct detection of the isomeric decay is the prior population of the excited

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Figure 2. Energy half-life distribution of isomeric nuclear states. Nuclear levels (blue circles) exhibit typical energies from a few 10 keV to several MeV. Only two low-energy (<1 keV) nuclear isomers are known: 229m-Th (~8.3 eV, shown as blue bar) and 235U (76.7 eV). Due to the too long radiative lifetime of 235U (ca. 10$^{22}$ s), only 229m-Th qualifies for a direct laser excitation and thus for the realization of a nuclear clock. In addition, selected clock transitions are included (red circles), which are already in use for optical atomic clocks. With friendly permission by Springer, Nature [6]. (Reprinted with permission from Physik-Journal (Wiley VCH, Germany), June 2020.)

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Nuclear Physics News, Vol. 31, No. 1, 2021
Figure 3. The low-energy part of the nuclear-level scheme of $^{229}$Th, used for indirect measurements of the isomer’s energy (from the double-difference of transition energies given in (a)). Part (b) contains key parameters of ground and excited states. The arrows mark possible decay paths of excited states. In the left part of (b) enlarged views of the ground state and the thorium isomer with their properties are displayed. (Reprinted with permission from Physik-Journal (Wiley VCH, Germany), June 2020.)

state, which can proceed in three different ways: (a) by a direct excitation of the isomer from the $^{229}$Th ground state. This could be achieved, for example, via synchrotron radiation [9] or applying a so-called electronic bridge process (EB) [10]. In the EB process the atomic shell will first be resonantly excited before it transfers its energy to the nucleus. (b) In a natural way through the $\alpha$ decay of $^{233}$U or the $\beta$ decay of $^{229}$Ac. Here one exploits that in both processes the isomer $^{229m}$Th will be populated by a decay branch (2% for $^{233}$U, 13.4% for $^{229}$Ac). (c) Via the population of a higher-lying nuclear state that populates the isomer in its decay (similar to the indirect measurements).

3. Besides the $\gamma$ decay, the thorium isomer can also decay to the ground state via the process of internal conversion (IC). Here the nucleus transfers its excitation energy to the atomic shell, resulting in the emission of an electron, provided that the ionization energy is smaller than the isomer’s excitation energy. With an isomeric excitation energy of 8.28 eV, this is only fulfilled for neutral thorium. These conversion electrons, emitted in the IC decay, were first detected in 2016 [6], now providing a method to determine the isomeric excitation energy via spectroscopic studies of the IC electrons [4].

Conversion Electron Spectroscopy

Determining the $^{229m}$Th excitation energy by conversion electron spectroscopy is based on a $^{229}$Th ion beam, which originates from the $\alpha$ decay of $^{233}$U. Since the thorium isomer will be naturally populated in this decay with a probability of 2%, a part of the $^{229}$Th nuclei will end up in the first excited state. The experimental setup is shown in Figure 4. The extraction of thorium ions (behind the buffer-gas stopping cell, predominantly in the $2^+$ and $3^+$ charge states) offers the advantage of the long isomeric lifetime of a few $10^3$ s, such that the thorium ions can be further manipulated. The reason for the long lifetime of charged thorium isomers stems from the fact that the otherwise dominant decay branch via internal conversion is energetically forbidden, which leads to a prolongation of the lifetime by up to nine orders of magnitude.

After their generation, the Th ions will be thermalized by collisions with ultra-pure helium gas in a buffer-gas stopping cell. Subsequently, an ion beam is formed by manipulating the ions through electrical fields, followed by purifying the beam from accompanying $\alpha$-decay products in a quadrupole mass separator. The same method was used for the first direct detection of the isomeric decay, whose signature is displayed in Figure 5a [6]. In order to improve the signal-to-noise ratio, the ions are first accumulated in a segmented linear Paul trap, to be then extracted in sharp pulses. This enables one to compare the time of the conversion electron detection with the start signal of the ion pulses, thus allowing derivation of the half-life of the thorium isomer.

In a first experiment the ions were collected on a metal surface in pulsed mode, leading to neutralization by charge exchange. This triggers the decay of the isomer by internal conversion, which is now energetically allowed. The low-energy conversion electrons could be registered time-resolved in a microchannel plate (MCP) detector. This led to the determination of the isomeric half-life of neutral thorium atoms to about 7 μs, as shown in Figure 5b [11]. In order to avoid any impact to the electrons’ work function by surface effects like electronic density fluctuations, the experiment was modified by realizing an in-flight neutralization of the Th ions when traversing a graphene foil. The kinetic energy of the IC electrons is then measured with a compact magnetic-bottle spectrometer [4]. Therefore, the electrons are first collimated in a magnetic bottle and then filtered according to their energy by a grid set to a repulsive electrostatic potential (Figure 4). Only electrons with a kinetic energy beyond a variable energy threshold can pass the grid and reach the MCP detector located behind. The isomer’s energy follows from the kinetic energy of the electrons plus the ionization energy needed to liberate the electron from the thorium atom (sufficiently well known to few meV). The resolution of the spectrometer allows for a determination of the isomeric energy with a precision of better than 0.1 eV. Moreover, the neutralization of thorium ions can end in excited atomic states, from where the subsequent IC decay of the thorium isomer as well will end in excited electronic states. This experiment provided the
first directly measured value for the excitation energy of the nuclear clock transition of 8.28 ± 0.17 [4]. At about the same time, in Japan, using synchrotron radiation, a first population of the isomer via resonant optical pumping into the second excited nuclear state of $^{229}$Th at 29.19 keV could be realized, which decays predominantly into $^{229m}$Th [12]. These results were used in Ref. [13], together with new γ-spectroscopic data, to derive an excitation energy of 8.30 ± 0.92 eV. Another value of 8.10(17) eV for the isomer’s energy was recently determined in Heidelberg [14] using a novel magnetic micro-calorimeter, in good agreement with the result of Ref. [4].
Laser-Spectroscopic Characterization

Besides precise knowledge of the excitation energy, another prerequisite for a nuclear clock is the possibility to monitor the nuclear excitation on short timescales. For this purpose, in 2003 a method was proposed, based on the double resonance principle [1]. It uses the different nuclear spins of ground and excited states to exploit the induced different hyperfine splittings in the atomic shell for identifying the two nuclear states. This isomer-induced hyperfine splitting could be experimentally detected in 2018 [15]. $^{229}$Th$^{2+}$ ions were stored in a Paul trap and the hyperfine splitting of a transition in the electronic shell was investigated by collinear laser spectroscopy. The experimental setup is shown in Figure 6, together with the excitation scheme [15]. The experiment was performed first with thorium ions exclusively in the ground state (Figure 6a), and second with $^{229}$Th$^{2+}$ from the $\alpha$ decay of $^{233}$U, thus being in 2% of the cases in the isomeric excited state (Figure 6b). A comparison of the resulting spectra reveals that in the second case, besides the expected lines from the ground-state hyperfine splitting, additional lines are observed, which can unambiguously be assigned to the nuclear isomer.

This observation not only allows for a nondestructive verification of the nuclear excitation, but resulted as well in a determination of the isomer’s magnetic dipole and electrical quadrupole moments and of the mean square charge radius (Figure 7). Based on these, the expected sensitivity enhancement of the isomeric transition for a potential temporal dependence of the fine structure constant $\alpha$ can be estimated. Theory predicted that the comparison of a nuclear frequency standard based on $^{229}$Th with an atomic clock could lead to a sensitivity enhancement by five to six orders of magnitude due to the low isomeric excitation energy compared to typical nuclear excitations [16]. Modifications of the fine-structure constant affect the Coulomb energy and could be detected with high sensitivity by a measurement of the isomeric excitation energy. The achievable sensitivity enhancement is determined by the Coulomb energy difference $\Delta V_C$ between ground and excited state that, however, cannot be calculated theoretically with sufficient precision. Predictions on $\Delta V_C$ strongly depend on the underlying nuclear models, which are not able to provide eV precision as required here. Nevertheless, an experimental value for $\Delta V_C$ can be inferred from the ratio of the quadrupole moments of ground and isomeric state and the ratio between the corresponding nuclear charge radii [17]. However, the first experiment did not yet result in a conclusive outcome [15].

Outlook

The recently achieved progress in the determination of the thorium isomer’s excitation energy, (1) directly inferred from the IC decay electrons as 8.28(17) eV (149.7 ± 3.1 nm) and (2) via $\gamma$-spectroscopic studies of higher-lying rotational levels (8.10(17) eV, corresponding to 153.1 ± 3.7 nm), marks a major milestone toward the realization of a nuclear clock. It remains to further refine this energy value with laser-spectroscopic methods in order to allow for the envisaged optical nuclear excitation.

In a first step, a broad-band laser can be used to localize the resonance with an accuracy of about 10 GHz (40 µeV). Using direct frequency-comb spectroscopy it will be possible to improve the accuracy in a second step into the

Figure 6. Concept to measure the $^{229m}$Th hyperfine splitting. (a) Experimental setup for Doppler-free laser spectroscopy of $^{229}$Th$^{2+}$ in the ground state (PTB trap). (b) Experimental setup for laser spectroscopy of $^{229}$Th with 2% in the isomeric state (LMU trap). (c) Two-step excitation scheme for Doppler-free spectroscopy of $^{229}$Th$^{2+}$. The 29,300 cm$^{-1}$ line is excited by two lasers (violet and red) and fluorescence is registered. A third laser (blue) is used to control the number of ions stored in the Paul trap for normalization purposes. With friendly permission by Springer, Nature [15].
In first-phase experiments on $\gamma$, conversion electron and fluorescence spectroscopy will be performed, not yet requiring highly precise knowledge of the isomer’s resonance energy and finally leading to a consolidation of the properties of the thorium isomer (transition energy, lifetime, nuclear moments, hyperfine structure, electronic bridge processes). The second project phase will focus on the laser-spectroscopic resonant excitation and spectroscopy of the thorium isomer in various electronic environments for ions in a trap as well as in a solid-state environment. Finally, it is planned to make one or even several nuclear clocks available for fundamental tests (e.g., variation of fundamental constants or search for ultra-light dark matter candidates). The nuclear clock will complement highly precise optical atomic clocks, while in some areas in the long run it might even have the potential to replace them.

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Atomic nuclei are made of strongly interacting protons and neutrons (nucleons), which are themselves made of quarks and gluons (partons). One of the overarching goals of modern nuclear physics research is to connect the low-energy-scale nucleonic picture of atomic nuclei with the underlying high-energy-scale partonic picture.

A promising avenue to understand the physics that lies between the two scales is to measure dynamic fluctuations of two-nucleon Short-Range Correlations (SRC): pairs of strongly interacting nucleons whose distance is comparable to their radii. Due to their overlapping quark distributions and strong interaction, SRC pairs can serve as a bridge between low-energy nuclear structure, high-density nuclear matter, and high-energy quark distributions with important consequences for many-body nuclear systems [1], strong-interaction physics [2], and the partonic structure of nucleons [3].

Here we present an overview of recent SRC measurements and their implications for our understanding of nuclear physics across scales: from many-body dynamics of asymmetric nuclei, through Nucleon-Nucleon (NN) interaction studies at high nuclear densities, to the partonic structure of nucleons bound in nuclei.

These results come primarily from an extensive set of SRC studies using high-energy electron scattering measurements. These experiments were performed at the Thomas Jefferson National Accelerator Facility (JLab) [4] in Virginia, USA, where the scattered electron was detected in coincidence with one or two nucleons emitted in the hard breakup of an SRC pair (Figure 1, left) [1–3, 5].

We also discuss a new generation of “inverse kinematics” SRC measurements, where high-energy nuclear beams are scattered from stationary hadronic probes (Figure 1, right). These studies are carried out at European (Joint Institute for Nuclear Research [JINR] and Gesellschaft für Schwerionenforschung [GSI]) and Japanese (Institute of Physical and Chemical Research [RIKEN]) facilities, and allow measuring radioactive nuclei relating to nuclear astrophysics. Results from these measurements, together with those from the fixed-target U.S. electron scattering program, are revolutionizing our understanding of short-ranged nuclear interactions, their impact on many-body nuclear dynamics,
and the manifestation of quark–gluon degrees of freedom in nuclei, while paving the way for experiments at the forthcoming Electron Ion Collider (USA) and the Facility for Antiproton and Ion Research (Europe).

Many-Body Nuclear Structure and Dynamics

Early studies of SRCs in nuclei from $^4$He to $^{208}$Pb have shown that they are predominantly proton–neutron (pn) pairs and that they account for almost all the high-momentum nucleons in the nucleus (where high is measured relative to the nuclear Fermi momentum, $k_F$) [7–9]. Again, we saw two separate scales: The interaction between the nucleons in the pair was observed to be very strong while the interaction between the SRC pair and the residual A-2 nuclear system was observed to be weak, leading to small pair center-of-mass (c.m.) momentum and a high pair-relative momentum [10]. Due to their high relative momentum, SRCs are also expected to account for most of the kinetic energy carried by nucleons in the nucleus, when evaluated in a high-resolution nuclear model.

The predominance of pn–SRCs (Figure 2, left) can lead to interesting effects in very neutron-rich nuclei. When adding neutrons to a symmetric nucleus, pn dominance is maintained if either the added excess neutrons do not form SRC pairs or if they interact to form SRC pairs with protons in the symmetric core of the nucleus. In the second scenario, as the neutron-to-proton (N/Z) ratio increases the proton correlation probability will grow. This would imply that adding neutrons will increase the average proton kinetic energy via formation of pn–SRC pairs.

To test this, we measured high-energy electron-scattering off SRC pairs in nuclei from C to Pb, with neutron–proton ratios N/Z ranging from 1 to 1.5, detecting the scattered electron in coincidence with a knocked-out proton or neutron in the CEBAF Large Acceptance Spectrometer (CLAS) [11]. The extracted fraction of high-momentum protons and neutrons in neutron-rich nuclei relative to a symmetric $^{12}$C reference is shown in Figure 2 (right). The results [1] indicate that, while the fraction of high-momentum neutrons saturates or slightly decreases with increasing N/Z, the fraction of high-momentum protons grows approximately linearly with N/Z. This supports the scenario where outer shell neutrons form pn–SRC pairs, increasing the average proton kinetic energy. This indicates momentum-sharing inversion in neutron-rich nuclei and can even impact the nuclear charge distribution in these nuclei [12].

As electron-scattering studies are limited to stable nuclei where the nuclear asymmetry generally increases with nuclear mass, it is difficult to cleanly separate the individual effects of nuclear asymmetry and nuclear mass. Therefore, in order to study SRCs along isotopic chains and in very neutron-rich nuclei reaching out to the drip-line, one must develop a program at radioactive-ion beam facilities. This is a paradigm change in the experimental technique used to study SRCs, including both a transition from “normal” to “inverse” kinematics and a change from a weakly interacting electromagnetic probe to a strongly interacting hadronic probe [13, 14].

Figure 2. (Left) Extracted ratios of pp– to pn–SRC pairs plotted versus atomic weight A, corrected for single charge exchange reactions (green points), showing the pn predominance. Figure taken from Ref. [9], with permission. (Right) High-momentum fractions for neutrons and protons relative to carbon. Red and blue rectangles show the range of predictions of a phenomenological pn-dominance model for proton and neutron ratios, respectively. Figure taken from Ref. [1], with permission.
This new approach was recently pioneered by the BM@N collaboration that performed the first test-measurement with a 48 GeV/c 12C ion-beam scattering off stationary protons in a liquid hydrogen target. The experimental setup is shown in Figure 1 (right). It consists of a nonmagnetic two-arm spectrometer to measure large-momentum transfer (p, 2p) reactions, and a nuclear-fragment detection system that is based on a large-acceptance dipole magnet. The SRC pair is probed in a proton-knockout reaction (p, 2pN) 10 B/10 Be that breaks up the pair and leaves the scattered protons, the pair recoil nucleon, and the heavy A−2 fragment to be detected in coincidence. Single-proton quasielastic knockout-reactions, leading to bound 11B, served as a reference channel, demonstrating that nuclear-fragment tagging selects the “transparent” part of the reaction and suppresses distortions due to initial- and final-state interactions, an essential feature to probe nucleon distributions using strongly interacting hadronic probes.

The experiment measured 23 pn– and 2 proton–proton (pp)–SRC breakup events with a bound A−2 spectator nucleus, confirming pn–SRC predominance. The kinematically complete nature of the measurement also allowed us to directly, and independently, probe the interaction of the nucleons in the pair, and the interaction between the pair and the residual nuclear system. The momenta of the initial nucleons in the pair were correlated back-to-back, the hallmark of a strong pairwise interaction, but the angle between the pair relative and c.m. momenta was isotropic, indicating complete factorization (separation) of the SRC wave function from that of the residual many-body A−2 system (see Figure 3). The data agree well with theoretical calculations using the Generalized Contact Formalism (GCF) [15–17] that, like all effective SRC models [5, 18], assumed the aforementioned factorization. This result is the first evidence for that major ingredient bolstering our understanding of SRCs.

This first experimental study of SRCs in inverse kinematics demonstrates the feasibility to access pairs in such kinematical conditions at large beam energies using a hadronic probe, with the additional advantage of measuring the heavy fragment, and thus uniquely the fourfold coincidence of the pair breakup in the future. A next generation of high-statistics experiments is already planned for the coming years using stable and radioactive nuclear beams at JINR and GSI, using nucleon pick-up reactions with radioactive beams at RIKEN.

**Figure 3.** Angular correlations in (p,2p) SRC breakup events. Distributions of the cosine of the angle between (a) the recoil nucleon and missing momentum and (b) 10B fragment and pair relative-momentum. Data (black points) are compared with GCF predictions (orange lines). Figure taken from Ref. [6], with permission.
The data are consistent with the theoretical GCF predictions, indicating the die-out of the tensor interaction and the onset of a scalar repulsive core at ∼800 MeV/c. Forthcoming experiments at Jefferson Lab [24] will measure single- and two-nucleon knockout data for a variety of nuclei (symmetric and asymmetric) with an order of magnitude larger statistics than any previous experiments. These data will allow for a detailed mapping of the tensor-to-scalar transition for pn and pp pairs with high precision up to missing momenta of 1 GeV/c, allowing for a detailed study of the repulsive core of the NN interaction.

**Nucleon Partonic Structure**

Last, we examine the relation between SRCs and the quark–gluon structure of nuclei. Experiments at the European Centre for Nuclear Research in the early 1980s showed that the fractional momentum distribution of quarks is modified when in a bound nucleon compared to a free one. This was surprising because the nuclear binding-energy scale is so much lower than the energy and momentum transfers in deep inelastic scattering (DIS). In a simple picture, valence quarks seem to slow down inside nuclei, slowing down more in larger nuclei. Even decades after its discovery, there is still no universally accepted explanation for the origin of this “EMC” (European Muon Collaboration) effect [5, 29], despite a large number of high-precision measurements in a wide variety of atomic nuclei [3, 30].

A correlation observed between the magnitude of the EMC effect and the relative amount of SRC pairs in different nuclei [3, 5, 31, 32] suggests that the EMC effect is driven by the modification of the internal structure of nucleons in SRC pairs and that SRC pairs could be the bridge between the low-energy nuclear scale and the high-energy DIS scale. Since nucleons in SRC pairs have a large spatial overlap between their quark distributions and are highly off-shell (\(E^2 \neq p^2 + m^2\)), it could allow for breaking the different scales of partons bound in a nucleon and nucleons bound in a nucleus.

Indeed, recent analysis of world data demonstrated [3, 25] that the EMC effect in nuclei from \(^3\)He to lead can be fully explained via a universal modification of the partonic structure of nucleons in SRC pairs. This modification is nucleus independent (universal) and the magnitude of the EMC effect in different nuclei depends only on the total number of SRC pairs in each nucleus. The Universal Modification Function (UMF) of nucleons in SRC pairs is shown in Figure 5 (left) [25].

In a recent analysis [28] the UMF model was extended to study the virtuality dependence of the modification of the bound nucleon structure. The analysis examined dif-
different characterizations for this dependence to find that existing data can be explained by a large number of such functions (see Figure 5, right). This calls for a new experimental program to measure “spectator-tagged deep inelastic scattering” (STDIS). In these experiments, electrons will be scattered off one nucleon in deuterium, studying its partonic structure and breaking it apart. At the same time, detectors placed at large backward angles from the momentum transfer will measure the correlated spectator nucleon, whose momentum, \( p_s \), is equal and opposite to the initial momentum of the struck nucleon \( p_i = -p_s \). This lets us measure how the partonic structure of bound nucleons varies with their momentum, which will provide the ultimate test of the EMC effect and its relation to SRC pairing. An initial STDIS measurement had insufficient statistics [33]. A second-generation STDIS measurement with a dedicated Back Angle Neutron Detector recently completed data-taking at JLab, with more measurements planned [26, 27]. These experiments should allow us to finally understand the origins of the EMC effect and to bridge the gap from the low-energy nuclear scale to the high-energy partonic scale.

Summary

Studies of high-momentum, short-distance nucleons in the nucleus cross several scales. These nucleons, which are almost entirely in two-nucleon short range correlated pairs, appear to bridge the gap between the nuclear binding energies at low energy and deep inelastic scattering from partons at high energy. At the same time, we can exploit the scale separation between the strong forces between the nucleons in the SRC pair and the much weaker forces between the SRC pair and the rest of the nucleus, to understand SRC pairs by developing a factorized description of them.

Recent experiments have revealed an extraordinary amount of information about these pairs, showing that they are dominated by pn pairs interacting via the tensor force at 300 to 600 MeV/c, but that the scalar force becomes dominant at higher nucleon momenta. This pn dominance increases the momentum of the minority protons in neutron-rich nuclei, possibly even causing them to have greater average momentum than the majority neutrons, an inversion of the classic Fermi-gas model result. New calculational techniques, using the GCF with significant input from \textit{ab-initio} many-body calculations, allow us to quantitatively describe SRC pairs, even up to 1 GeV/c of momentum. Finally, new experimental techniques, including using energetic ion beams in inverse-kinematics and STDIS, will allow us to study SRC pairing in unstable nuclei and the origins of the EMC effect.
feature article

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*Nuclear Physics News, Vol. 31, No. 1, 2021*
Toward Machine Learning Optimization of Experimental Design

Introduction

The design of instruments that rely on the interaction of radiation with matter for their operation is a quite complex task if our goal is to achieve near optimality on some well-defined utility function $U$, such as the expected precision of a set of planned measurements achievable with a given amount of collected data. This complexity stems from the interplay between physical processes that are intrinsically stochastic in nature—the quantum phenomena that take place at the subnuclear level—and the vast space of possible choices for the physical characteristics of the instrument and its detection elements, as defined in its design phase. The precision of pattern recognition of detected signals and the power of information-extraction procedures that directly affect the value of $U$ both depend on these characteristics. In the majority of realistic cases, $U$ may be represented as a combination of performance and cost considerations that should be balanced within reasonable limitations.

Neural networks are naturally suitable for the task mentioned above [1]. They can also be effectively used as surrogates for simulators to enable gradient-based optimization in cases where a simulator is nondifferentiable. In addition, automatic differentiation (AD) techniques developed in the 1980s [2] and now commonly available in the most popular machine learning (ML) frameworks [3] make it possible to rely on efficient implementations of the back-propagation algorithm. The MODE Collaboration (MODE) aims at developing tools based on deep neural networks and modern AD techniques to implement a full modeling of all the elements of experimental design, achieving end-to-end optimization of the design of instruments via a fully differentiable pipeline capable of exploring the Pareto-optimal frontier of $U$. Exploratory studies have shown that very large gains in performance are potentially achievable, even for very simple apparatus [5, 6].

MODE has the goal to show how those techniques may be adapted to the complexity of modern and future particle detectors and experiments, while remaining applicable to a number of applications outside of that domain. Below we succinctly describe the research program of the MODE Collaboration.

The MODE Program

Architecture Development

A generic optimization pipeline for a complex system can be constructed by assembling modules that take on different modeling tasks. The modules interact by receiving input data and processing them to provide an output that satisfies specified external constraints dependent on the value of the parameters under study; the output of each module is fed to the next one, until an objective function can be computed. The computation of each module is differentiable, so that the composition of such modules is also differentiable through the chain rule of differentiable calculus, enabling the gradient of $U$ to be computed and used in the search for extrema of the objective function [7]; the search may be performed in steps, by freezing some modules while updating others, to simplify the parameter space scan.

For a specific example we may consider the optimization of the layout of a muon radiography [8] apparatus for material identification within a volume of interest (one of the use cases described below). A random generation of cosmic rays, in the form of incoming particle four-vectors, is fed to a fast simulation of detection apparatus and scanned volume. The simulation of multiple scattering, particle propagation, and resulting electronic signals in the detector may be directly produced by a differentiable program. Alternatively, the simulation output may inform a differentiable module based on deep generative models, such as variational autoencoders (VAE) [9], generative adversarial networks (GAN) [10], or flow models [11], or through the use of local generative surrogates of the gradients [6]; a generation/validation loop must be available to adjust the model, as the layout parameters are modified during the optimization task. The output of the particle detection module is fed to a reconstruction module, which produces incoming and outgoing track measurements through a fit to the detected signals; these are again a function of the detector parameters. Downstream, an information-extraction module accumulates information on the density of material in the container. Its output may be used to compute a loss function that describes as closely as possible the real goal of the system. In a simplified setup this function could be defined as the type-II error rate on the detection of a given amount of a particular material within the volume of interest, as modeled by the simulation. A sketch of the described pipeline is shown in Figure 1.
Use Cases

Given its considerable complexity, the development of a pipeline for the optimization of experimental designs should start with the study of simpler use cases, and proceed incrementally by adding complexity. Below we succinctly exemplify a set of use cases that might be considered in series in the development of our research plan.

The MUonE Detector

MUonE is a detector proposed to measure precisely the $q^2$-differential cross-section of elastic muon-electron scattering, to reduce dominant systematic uncertainties in the “g-2” experiment [12]. Given the simplicity of investigated physics process and baseline detector layout, MUonE was taken as an example for geometry optimization studies that did not employ AD techniques [5]. A reanalysis within a full feedback loop that considers all geometry parameters together with reconstruction-driven systematic uncertainties, cost, and a more precise definition of the utility function is relatively straightforward to produce, and may thus constitute a valid initial benchmark for comparison of automatic optimization searches and discrete scans.

Muon Radiography

The abundant natural flux of atmospheric muons and their large penetration power have been exploited for the imaging of a large variety of objects spanning in size from $O$(m) to $O$(km), with applications including archaeology, volcanology, border control, nuclear safety, and industrial process control [8]. In some applications, the volume of interest can be sandwiched between two trackers and one can measure the scattering of the muons through the target volume, which is correlated with the atomic number $Z$ of the material. When the target volume is very large (e.g., a mountain or an entire building), a single tracker is placed downstream to measure the absorption of the muon flux through the target, from which a density map can be derived. By optimizing the layout of the detectors, large gains in the resolution and material identification potential of a muon tracking system are achievable. A recent project [13] aims at the development of compact, autonomous, portable, and modular muon radiography setups based on small-area resistive plate chambers (RPC), a technology chosen because of its good trade-off between cost, ease of construction, and position and time resolution. The goal is to allow a high degree of modularity for the geometry of the complete setup: ideally, the already mounted individual RPC planes would be produced in large numbers and deployed in situ in the arrangement that best fits the specific use case while respecting the local constraints (e.g., the optimal location may be in a narrow tunnel). The same RPC layers may be arranged to form one or two trackers depending on the relative importance of absorption and scattering on the final discrimination power; for a single tracker sometimes it is not obvious a priori whether it is more convenient to have a few layers with large areas to collect more data, or to maximize the number of layers crossed by the muons to improve tracking resolution. An automatic optimization algorithm would be able to provide a quick redesign of the geometry for new measurements of different targets.

Proton Therapy

Effective irradiation of nonoperable tumors with intense proton or light-hadron beams could be achieved if rapid imaging techniques are used to create 3-D maps of the target and surrounding tissue. The imaging resolution depends on the possibility of acquiring sufficient data within seconds, avoiding target movements. A fast calorimeter has been developed by the iMPACT Collaboration [14] for this effort. The optimization of the layout of the detection elements, and the optimal addition of a magnetic field to the setup, are important aspects well suited to an investigation with AD
means. We plan to collaborate with iMPACT to investigate the space of detector solutions, with the goal of maximizing the benefit of the imaging tool produced.

A Hybrid Calorimeter for a Future Collider

So far, the guiding principle when building high-energy physics detectors has been strongly governed by the idealized requirements of classic reconstruction algorithms. As a consequence, general-purpose detectors follow the principle of tracking charged particle trajectories within a magnetic field in a low-material-budget tracker, where nuclear interactions and multiple scatterings are kept to a minimum to provide good conditions for the track helix fit; only in a second step are both neutral and charged particles brought to a stop to measure their energy in a dense calorimeter. With recent advances in machine-learning-based particle reconstruction from raw detector signals [15], it is possible to break this paradigm and optimally combine position and energy measurements. We foresee the exploitation of these advancements with the study of feasibility and design of an optimized hybrid calorimeter, with material density increasing with distance from the interaction point. Such a device would ideally allow one to exploit the distinct nuclear interactions of different particle species with the material together with the probabilistic information from a detailed tracking of the evolving shower through the detector. However, this approach would require an optimization of the hybrid reconstruction before its inclusion into the global optimization pipeline [16]. Creating a precise, fully differentiable model for the optimization of such a system is a terrific challenge, with possible enormous gains.

Computing and Infrastructure Requirements

The basic pipeline should be generic and customizable for different detector optimization problems, and have a well-defined structure of encapsulated functional blocks. This enables running blocks separately for the initial decomposition of the full problem, as well as validation of individual blocks. The pipeline optimization loop should use containerization technologies and be runnable on common computing infrastructure. Various blocks use gradient optimization underneath, thus access to accelerated tensor computing hardware is essential. The infrastructure should provide an interface for the communication of input/output values for every block. The optimization target should be flexible to support a variety of constraint metrics, such as physics performance, detector performance, and cost; in cases when multiple criteria are specified, a Pareto-optimal selection of possible configurations should be returned. Besides optimized detector parameters, the pipeline should produce trained surrogate models and reconstruction algorithms suitable for interactive analysis of possible trade-offs between alternative options. The infrastructure should also allow users to substitute any ML-powered block with a reference baseline implementation of the same functionality. This provides a direct way for collecting reference data to train the surrogate models ML implementations, as well as for validating and evaluating the corresponding blocks. The framework should also support tuning of ML models using a combination of real and simulated data.

Concluding Remarks

Recent advances in computer science make it possible to give a truer meaning to the word “optimization” when discussing the design of instruments that operate via the interaction of radiation with matter. The MODE Collaboration aims at developing a versatile, modular, and scalable software architecture that can be customized to different optimization problems and provide a full exploration of the space of their design choices and information extraction procedures. We believe that such a tool may offer enormous potential gains to a wide range of research and industry applications.

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facilities and methods


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How Theoretical Nuclear Physics Can Help Discover New Drugs

Introduction
Over the last century, theoretical nuclear physicists have been developing and testing approximation methods and numerical techniques to investigate the structure and dynamics of strongly interacting quantum systems. Some of these powerful schemes have been successfully applied to other fields where nonperturbative phenomena are relevant, including condensed matter physics and quantum chemistry. On the other hand, cross-disciplinary applications of nuclear theory methods to soft-condensed matter and biophysics have been relatively less frequent, mostly because quantum effects in these systems are often negligible. In this article, we discuss how a path-integral-based approach, originally developed for quantum chromodynamics (QCD), has been adapted and successfully applied to investigate the structural dynamics of biological macromolecules. In particular, this cross-disciplinary research paved the way to simulating for the first time the folding of large biologically relevant proteins using realistic all-atom models. Some unexpected biophysical information that emerged from these simulations led to conceiving a completely new paradigm for rational drug discovery, which is now being industrially pursued and may help tackle pathologies that are currently untreatable.

Undruggable Proteins
The most common approach to drug discovery is based on identifying small molecules that are able to bind to specific target proteins, thus inhibiting their biological function. Unfortunately, however, some proteins are considered “undruggable.” For example, this can occur when the three-dimensional protein structure does not display a suitable “pocket”; that is, a concave region where a small molecule can bind in order to interfere with the biological function. Other proteins are undruggable because they occasionally assume aberrant forms, which then lead to very stable and toxic aggregates. Clearly, developing entirely new approaches for drug discovery is extremely important to envision therapeutic strategies for currently untreatable diseases.

Protein Folding
From a chemical point of view, proteins are polypeptide chains made of 20 different types of amino acids. However, the specific sequences of amino acids that are found in proteins have very peculiar properties. Namely, while most sequences of amino acids give rise to a glassy energy landscape, typical of random heteropolymers, protein sequences generate a funneled energy landscape, with a single stable minimum, called the native state. As a consequence, immediately after they are synthesized, proteins begin to fold (i.e., to surf down the energy funnel until they reach their native state, where they finally become biologically active).

Understanding the folding mechanism is of course a key problem in biophysics, with countless implications, ranging from molecular biology to pharmacology and nanotechnology. Unfortunately, while X-ray crystallography and Nuclear Magnetic Resonance (NMR) experiments can determine protein native structures with an atomic level of resolution, none of the existing experimental techniques can yield dynamical information with a comparable level of spatial resolution. As a consequence, to date, computer simulations are the only available tools to gain atomic-level insight into protein folding.

Unfortunately, computer simulations of protein folding are also extremely challenging. The main reason is that the transition from a swollen chain configuration to the native state requires overcoming a large free-energy barrier. Consequently, successful folding transitions are extremely rare events, which occur at rates that can span from once every few milliseconds to once every several minutes, depending on the specific chain.

Such a huge decoupling of time scales is the ultimate reason why plain molecular dynamics (MD) simulations of biologically relevant protein folding processes are doomed to remain unfeasible for many years to come. Notable exceptions are a handful of mini-proteins, specifically engineered to fold within submillisecond time scales. In 2011, the private company D.E.S. Research reported results of an ultralong MD simulation of the 12 fastest folding proteins. These were performed on a special-purpose supercomputer called Anton, specifically designed to perform only MD simulations [1]. While this selected set of mini-proteins has no biological relevance, the observation of several spontaneous unfolding/refolding events in the simulation provided the evidence that current atomistic models...
are accurate enough to recognize protein native states. However, even using the Anton supercomputer, the observation of a single folding event for a typical biologically relevant protein may require hundreds or even thousands of years of simulation.

QCD-Inspired Approaches to Protein Folding

In order to tackle this hard-core limitation of MD, many more advanced enhanced sampling algorithms have been developed in the last two decades. In particular, an inspiration for adapting some approximation originally developed in nuclear physics came from the observation that the phase diagram of proteins in solution displays several intriguing analogies with that of QCD (see Figure 1). For example, at low temperatures and low concentration of chemical denaturants (e.g., urea) proteins are found in a low-entropy phase, in which the relevant conformational degrees of freedom are frozen. At high temperatures or high denaturant concentration, proteins undergo a melting transition into a high entropy phase, in which new conformational degrees of freedom are released. It is also interesting to note that only very specific combinations of amino acid sequences can generate funneled energy landscapes. This phenomenon, known in the literature as the Minimal Frustration Principle, may be interpreted as a classical type of confinement, in the space of the 20 amino acid “colors.”

The structure of the QCD vacuum contains gauge fields generated in quantum tunneling events between degenerate classical ground states. The natural mathematical framework to describe these events is the so-called Instanton Calculus, which is based on the imaginary-time Feynman path integral formalism. Interestingly, also rare thermally activated structural transitions of macromolecules can be represented by an almost identical path integral. Namely, it is possible to rigorously express the probability for a chain to go from some given initial unfolded configuration $x_U$ to the native configuration $x_N$ as a functional integral over all possible folding pathways. From here came the idea of adapting the Instanton Calculus to address the protein folding problem [2, 3].

A major advantage of the path integral approach to protein folding is that it avoids wasting an exponential amount of computational time to simulate uninteresting thermal oscillations in the initial unfolded state. Instead, it enables one to sample directly the so-called transition path ensemble (i.e., to focus on the barrier-crossing part of the dynamics). The prize to pay for this major simplification is that of having to provide in input the full three-dimensional structure of the final protein conformation, $x_N$. Therefore, while path integrals can be useful to compute the relevant folding pathways, they cannot be used to predict the protein native structures.

The initial attempts to adapt Instanton Calculus to protein folding problems led to algorithms that turned out to be too inefficient to be applicable to biologically relevant proteins. However, the same path integral formulation offered a platform to develop new variational schemes [4, 5] and self-consistent mean-field-type approaches [6]. Some of these methods were found to be extremely computationally efficient, enabling the simulation of a very large class of biologically relevant proteins. Through a number of detailed validation studies it was shown that these methods provide predictions in quantitative agreement with experiments (see, e.g., Ref. [7]) and with the available MD simulations (see, e.g., Ref. [8]).

Equipped with this new, powerful, virtual microscope, a few years ago we embarked in different multidisciplinary collaborations, aiming at unveiling different biophysical aspects of protein folding. In particular, a series of investigations performed in collaboration with the laboratory of E. Biasini at Trento University revealed

![Figure 1. Phase diagram of proteins in solutions.](image-url)
A surprising fact: almost all biologically relevant proteins simulated with our methods were found to fold by visiting a rather well-conserved sequence of partially folded meta-stable states, called folding intermediates. This finding contrasts with the folding mechanism of small proteins, which usually occurs via a simple two-state transition. The idea that the folding of biologically relevant proteins could be far more complex than that of mini-proteins had been already suggested, but such folding intermediates were never systematically observed and characterized with atomistic detail.

A New Paradigm for Rational Drug Discovery

This finding immediately raised the question whether folding intermediates may have a functional role in biology. A related question is whether it is possible to leverage on the knowledge of folding intermediates to find new ways of inhibiting potentially harmful proteins. This question led to conceiving and patenting a radically new approach to rational drug discovery, called Pharmacological Protein Inactivation by Targeting Folding Intermediates (PPI-FIT) [9, 12]. The basic idea behind this scheme is to look for small molecules (i.e., potential drugs) that can bind to the target protein before it reaches the native state (i.e., when it is still stuck in some of the theoretically predicted folding intermediate). Cells are equipped with a quality control machinery that enables them recognize and eliminate partially or incorrectly folded proteins, through a process called protein degradation. This way, undruggable proteins may become druggable.

This new paradigm for computer-based drug discovery was first validated on the human prion protein (denoted as PrP\(^\text{C}\)). This polypeptide chain represents the substrate of infective agents called prions, consisting of toxic aggregates of misfolded prion proteins, denoted as PrP\(^\text{Sc}\). Prions are responsible for several invariably lethal neurodegenerative diseases, including the infamous mad cow disease. By reducing the concentration of PrP\(^\text{C}\) in cells, one can hope to hamper the accumulation of toxic aggregates of PrP\(^\text{Sc}\), thus stopping or at least slowing down the prion infection. Unfortunately, PrP\(^\text{C}\) proteins are considered undruggable by conventional drug discovery techniques.

However, the application of PPI-FIT led to the discovery and patenting of several small molecules that have been demonstrated to effectively reducing the expression levels of PrP\(^\text{C}\) proteins in cells, in a clear dose-dependent manner. This result is illustrated in Figure 2, for a specific small molecule called SM875. Using a biochemical method called Western Blotting it is possible to determine the abundance of a given protein in a cell. In addition, fluorescence spectroscopy can be used to tag proteins and provide a tomographic map of their location in cells. The inset in Figure 3 shows that the relative abundance of human PrP\(^\text{C}\) decreases with an increasing concentration of SM875. The green dots in the black background correspond to PrP\(^\text{C}\) proteins. In ordinary physiological conditions, PrP\(^\text{C}\) are mostly found anchored to the cell membrane. This is why the green lines in the leftmost panel highlight the shape cellular contours. However, after the exposure to SM875, PrP\(^\text{C}\) chains cannot complete the folding process and are no longer able to reach the cellular membrane. Instead, they accumulate in regions located in the cell interior, which may be associated with degradation centers. The industrial application of the PPI-FIT technology is now being pursued by Sibylla Biotech S.R.L. (www.sibyllabiotech.it), a research spinoff of
impact and applications

the Universities of Trento and Perugia and of the Italian Institute for Nuclear Physics (INFN).

Anti-COVID 19 Action

Using PPI-FIT, researchers at Sibylla Biotech have already identified a number of small molecules, actively reducing expression levels of proteins relevant in different therapeutic areas. In particular, after the burst of the COVID-19 world pandemic, Sibylla Biotech and INFN have joined forces to look for an antiviral drug for severe acute respiratory syndrome–type viruses. In particular, INFN has contributed by making available its computing infrastructures, normally employed for data analysis in Higgs boson–related research. Using these computational resources, scientists at Sibylla were able to quickly simulate the folding of Angiotensin-coverting enzyme 2 (ACE2), a large protein recognized by the SARS-COV2 virus in the early stage of the COVID-19 infection. The hope is that reducing the cellular expression levels of this protein may hamper the ability of the COVID-19 virus to penetrate the cell membrane and propagate the infection.

By applying the PPI-FIT approach, Sibylla’s researchers discovered that a few drugs that are already FDA approved for different therapeutic purposes can actually reduce ACE2 expression levels. Later experiments performed on pseudoviral vectors confirmed that reducing ACE2 expression levels can contrast viral infections [10]. Finally, experiments of specific cellular lines infected with COVID-19 are currently being performed.

A Look Into the Future

In spite of these successful applications, many fundamental biophysical process (e.g., allostery transitions) remain too complex to be simulated with the present technologies. To overcome these limitations, we are currently working on integrating our theoretical physics methodologies with two new emerging and enabling technologies: automated learning and quantum computation. A first step in this direction has already been made [11], placing the seed for several possible developments in the forthcoming years.

In conclusion, this long research journey illustrates well how the relevance of nuclear physics extends much beyond its natural cultural perimeter. Indeed, the intrinsic complexity of this field makes it an ideal ground to devise innovative cross-disciplinary approaches, which may have potentially relevant implications in society.

Disclaimer

Pietro Faccioli is co-founder and shareholder of Sibylla Biotech SRL, a company exploring computational simulations to perform rational drug discovery.

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Figure 3. In the inset: SM875 reduces cellular expression levels of human prion protein in a dose-dependent manner. In the background: after exposures to SMS875, PrPc chains no longer reach the cell membrane and accumulate in the cell (see discussion in the main text).
IPAC20, the First Virtual International Particle Accelerator Conference

The IPAC20 story began in February 2015 when the Grand Accélérateur National d’Ions Lourds (GANIL) in Caen, France decided for the second time to bid to host the prestigious International Particle Accelerator Conference (IPAC) conference, bringing together 1,300 members of the particle accelerator community. This yearly conference takes place every three years in one of the European countries. IPAC is the most important world conference in the field of accelerators.

In the past, it has always been held in large cities: 2010: Kyoto (Japan), 2011: San Sebastian (Spain), 2012: New Orleans (USA), 2013: Shanghai (China), 2014: Dresden (Germany), 2015: Richmond (USA), 2016: Busan (South Korea), 2017: Copenhagen (Denmark), 2018: Vancouver (Canada), 2019: Melbourne (Australia), 2020, and the organization of the IPAC20 in Caen, Normandy, France, 11–15 May 2020, was a true challenge. Although there is no doubt about the attractiveness of the Normandy region, the enthusiasm of local organizers is not enough. To make the conference a success, the support of an event professional agency to guide the organization was necessary. A first national selection panel took place in the presence of representatives of CNRS/IN2P3, CEA/IRFU, SOLEIL, and the ESRF, and the GANIL/Caen proposal came out as the winner ahead of Paris, Lyon, and Strasbourg. The last step was the presentation of the proposal to the IPAC international committee on 4 December 2015 in Lund, Sweden. After the votes of the 35 representatives from 15 countries, the French candidacy won the competition. The local organizing committee was formed soon after, with 26 members representing 17 French laboratories or institutes. The organization is very well framed by the well-established international organization of IPAC conferences and its committee with Mike Seidel (PSI) and Ralph Assmann (DESY) as respectively the chair and the Scientific Program Committee chair.

The requirements to host the conference are commensurate with its prestige. A participation of between 1,300 and 1,700 scientists and 120 industrial exhibitors is expected. One hundred and twenty scholarships are usually awarded to help young researchers attend the conference.

Finally, a Joint Accelerator Conferences Website (https://www.jacow.org) editorial board with its 25 members is expected to publish up to 2,000 preprints during the conference. This behind-the-scenes work guarantees the quality of the proceedings. A peer review process has been in place for two years to increase the impact of the publications.

The first doubts on the feasibility to host the face-to-face conference appeared in mid-February 2020, following the evolution of the COVID-19 pandemic and a study of the first possible scenarios and economic consequences was necessary. France shortly after introduced a lockdown, on 17 March 2020. We immediately understood that with the international situation deteriorating and borders closing, speakers would not be able to come to the conference site. The decision was made on 19 March 2020 to host the conference as an on-line event. Even if the procedures for canceling contracts and services had to be initiated and reimbursements of fees already paid by participants to be made, our concern was to be able to capitalize on the four years of work. The remaining six weeks before the beginning of the conference allowed us to prepare a fully on-line conference.

Our first priority was to preserve the oral presentations and the foreseen conference prizes.

Thus, plenary and the accelerator-prize sessions were maintained, but unfortunately the poster and industry sessions had to be canceled. The proposed program included more than 2,000 submitted abstracts. It was condensed by the scientific program committee into 78 presentations with 40,000 video views across 60 countries, making IPAC20 one of the pioneers of virtual conferencing and a highlight scientific event during the lockdown.

The proposed conference format relied on pre-recorded presentations and a text-driven chat that allowed registered participants to engage with the presenters.
participants to attend discussions from all time zones across the world. Half-day sessions were organized in order to follow as much as possible the schedule of live presentations. A final live session, during which the four prizes of the accelerator group of the European Physical Society were awarded, was held in the end of conference.

IPAC20’s success relied on the excellence of its program with recent technical highlights, new developments, and future plans in the accelerator world.

The effort required to make IPAC20 a successful virtual event has been rewarded by a threefold increase in the number of participants and the presence of all the laboratories in the field. IPAC20 not only allowed us to forget the health crisis for a week but also highlighted the dynamism of our community with all our new projects and activities. This alternative conference format cannot completely replace the richness of direct human interactions, but facilitates and democratizes the participation of laboratories and students for whom travel costs might be a problem. There is no doubt that future conferences will be able to take advantage of hybrid formats.

The 12th IPAC conference is scheduled to take place in Brazil in 2021. We wish it a great success.

"Nucleodemic" Meeting NUCLEUS-2020

As a Russian proverb says, “There was no happiness, but misfortune helped.” It applies to the international conference “NUCLEUS-2020. Nuclear Physics and Elementary Particle Physics. Nuclear Physics Technologies,” held on-line October 12–17 (https://indico.cern.ch/event/839985/). Indeed, more than 550 participants from 38 countries attended this event virtually (the art collage for the NUCLEUS-2020 conference used machine learning technique and participant individual portraits that one can see at https://indico.cern.ch/event/839985/images/29873-groupPhoto2.jpg).

NUCLEUS-2020 was organized by St. Petersburg State University (SPbSU) in collaboration with the "Kurchatov Institute" and Joint Institute for Nuclear Research (JINR), and supported by the Nuclear Physics European Collaboration Committee.

This conference, the 70th in a row, is the eldest nuclear conference in Russia. Starting as a local meeting on nuclear spectroscopy in the early days of nuclear physics, it has evolved into
The beginning of the NUCLEUS-2020 anniversary session was initiated by welcome speeches by Paolo Giubellino, the director of the Society for Heavy Ion Research/Facility for Antiproton and Ion Research (FAIR) in Darmstadt; V. A. Matveev, the director of JINR (Dubna); S. V. Mikushev, vice-rector of SPbSU; and A. E. Blagov, the director of the National Research Center (NRC) Kurchatov Institute, who opened the scientific program by a report dedicated to the development of synchrotron and neutron research, a dynamically developing area of modern physics.

The plenary conference talks were dedicated to almost all cutting-edge advances in nuclear physics and particle physics: neutrino physics problems (Jiangmen Underground Neutrino Observatory collaboration, Germanium Detector Array collaboration, Petersbrug Nuclear Physics Institute (PNPI) neutrino program), studies of ultrahigh energy cosmic rays (Pierre Auger collaboration), low energy and nuclear fission physics, and modern detector technologies. Promising opportunities in neutron and nuclear physics from the launch of the new high-flux PIK reactor in Gatchina were demonstrated. The highest interest and the maximal number of the reports have been in the section of relativistic nuclear physics. The main high-energy physics collaborations—ALICE, CMS, ATLAS, NA61/SHINE, PHENIX, STAR, Facility for Antiproton and Ion Research, and Nuclotron Based Ion Collider facility (NICA)—presented their new physics and detector technology achievements.

The program on nuclear physics methods in medical research was expanded this year. The new method of therapy was presented as a promising treatment that nuclear medicine can offer. The other important topic of the nuclear medicine methods dedicated to radionuclide therapy and diagnose was raised by the SPbSU team in collaboration with V. G. Khlopin Radium Institute of Russian State Atomic Energy Corporation ROSATOM. They gave a review report on the combination of radionuclide imaging with radioisotopetherapy—“Theranostics” (a neologism resulting from therapy based on diagnostics). This method can give excellent results with minimal side effects in the fight against cancer illness.

The report about the experience of experts training with regard to nuclear medicine technologies was presented by colleagues from Moscow State University.

In conclusion, one can note that, despite thousands of kilometers and several time zones between us, we all followed the reports, asked questions of the speakers, and commented on their findings and discoveries. And, who knows, maybe these are the questions that will trigger new discoveries! “From dreams, to ideas and to discoveries”!

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Humanity and Physics Meet at Tenth Tastes of Nuclear Physics

For the last 10 years, the Tastes of Nuclear Physics has served as one of South Africa’s most successful conferences on fundamental nuclear physics and applications. The main goals are enthusing South African students toward their highest education and physics achievements by attracting world-class speakers to instruct them on timely topics in nuclear physics and nuclear astrophysics. Within the diverse and free academic environment of the historical University of the Western Cape (UWC) in the beautiful Cape Town, our students discuss physics and engage with the experts at any time throughout the Tastes, especially during the assigned coffee breaks and our famous homemade lunches and braais (lots of grilled meat!), which generally open new doors to exchange collaborations and physics ideas. No fees apply and everyone is welcome. The Tastes was hosted by the Univer-
The Tastes came last year (30 November–4 December 2020) with a new approach that transcends our difficult times. We went virtual, broadcasting to the entire world, reaching a total of 610 participants, about 60 world-class speakers, and collaborators from 21 countries. The combination of physics talks and South African musical interludes by the UWC and UNIZULU choirs created a much needed human touch and raised the spirits. The conference did not have a single connectivity issue during the five days. This was only possible because of the infallible dedication of UWC’s workforce (International Office, Institutional Advancement, Physics and Astronomy departments, and senior management). Special celebrations included our successful Honors/MSc program in nuclear and materials science; Women in Science; the Gamma-Ray Spectrometer for Knowledge in Africa (GAMKA) [2]; the Modern African Nuclear Detector Laboratories at UWC and UNIZULU; a joint collaboration with the University of York and the Science and Technology Facilities Council (STFC) in the United Kingdom; and Tastes Awards to South African students leading publications in top physics journals during 2019–2020. Talks and videos can be found at http://nuclear.uwc.ac.za/index.php/tastes-of-nuclear-physics/ and https://www.youtube.com/c/NicoOrce, respectively.

There is no better way to express what the Tastes means than by showing a few of the many appreciative comments received. Sally Hicks (University of Dallas) called the Tastes, “The most positive thing that happened in 2020.” A Ph.D. student told us that “the majority of my studies have been in COVID times so it was really nice to be able to attend such a wide variety of talks and interact with the nuclear community. I just wanted to show you my appreciation and let you know Tastes really was an experience like no other I have had since starting my Ph.D.” John Wood from Georgia Tech and UWC extraordinary professor has been coming to South Africa for all the previous editions and encourages newcomers: “You know how, when you sow seeds, you want to put the seeds where they’ll grow the best. That’s why I come here.” Of course you are all invited to join the Tastes next year. Our ethos: Let’s do Physics together!

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JINR Long-Term Development Strategy

The Joint Institute for Nuclear Research (JINR) has released the physics part of its Long-Term Development Strategy up to 2030 and beyond (https://indico.jinr.ru/event/1121/).

This Scientific Long-Range Plan (SLRP) is the fruit of more than two years of intense discussions by JINR scientists in a concerted action by the whole JINR physics community and international experts.

The process of development for the research strategy for the future of JINR was launched in 2017 with the establishment of an International Working Group of outstanding scientists—worldwide recognized experts in their field of research. Seven Working Sub-Groups spanning the areas of basic and applied science and technologies have been established: Low Energy Nuclear Physics, Relativistic Heavy-Ion and SPIN Physics, Particle and High-Energy Physics, Neutrino and Astro-Particle Physics, Condensed Matter and Neutron Nuclear Physics, Radio- and Astrobiology, Nuclear Medicine and Life Sciences, Theoretical Physics, Information Technologies and High-Performance Computing. In that way the subfields of modern science to be addressed in the future at JINR have been determined, and a broad representation of specific topics in the subfields was provided.

The Working Sub-Groups were given the charge to delineate the most exciting physics in their subfields, to highlight recent achievements, and to discuss the future perspectives.

A series of reports from the Working Sub-Groups were presented and discussed in a number of meetings of the JINR Scientific-Technical Committee and of the JINR Scientific Council in 2019. The editorial board was established in order to generate an integrated, balanced document.

Based on this work, the following SLRP emerged, where new facilities, those already under construction, and upgrades are presented. After an Executive Summary, the integral document features the development of the research on several important fields of science JINR has chosen to work in, with the intention to be at the forefront of these fields in the next decade(s).

The JINR directorate is very grateful for this intense, fruitful, and honest interaction between JINR scientists, their partners in JINR member states, and world-leading scientists, which helped formulate an ambitious vision for the medium- and long-term future of JINR. It is especially important to see the many young scientists who have contributed to this SLRP with ambitious goals and projects.

Furthermore, the institute will take all measures for strengthening its expertise in the latest technologies (e.g., micro-electronics, application-specific integrated circuit chip design, and detector design, as well as material research and accelerator technologies).

Large efforts are planned for the educational and training program to assure the continuous expertise and know-how needed for meeting the scientific and technical challenges ahead.

The SLRP of JINR is and will be an integral part of the European Strategy for Nuclear Physics, of the European and Worldwide Particle Physics Strategies, as well as of the Global Strategies of Astro-Particle Physics, Biophysics, and Neutron Research.

JINR scientists are looking forward with great hope that this plan will convince the JINR member states to seek avenues for accomplishing the objectives outlined in the SLRP.

JINR Committee of Plenipotentaries approved the SLRP in June 2020 and charged the directorate to continue the strategic planning toward development of the next JINR seven-year plan.

With this spirit, JINR can move forward as one of the largest basic research centers in the world.

Boris Sharkov
JINR Dubna
Jonathan Bagger Selected as CEO of the American Physical Society

The theoretical physicist Jonathan Bagger, director of TRIUMF in Vancouver, British Columbia, has been selected to succeed Kate Kirby as the American Physical Society (APS) chief executive officer (CEO). The APS board of directors unanimously approved the appointment in June, following the recommendation of the CEO Search Committee. Kirby retired from the top APS staff position at the end of 2020.

Bagger’s extensive experience in scientific management and his strong commitment to the APS and its critical mission in the physics community will serve the society well. Dr. Bagger took the helm of TRIUMF, Canada’s particle accelerator center, in July 2014. The laboratory has a staff of more than 500, and 1,200 users representing 40 countries. His leadership paved the way for the long-term future of the laboratory and brought new dimensions to its governance structure. He successfully steered the TRIUMF Five Year Plan 2020–2025, securing stable finances and strengthening its scientific program, especially in advancing the completion of Advanced Rare Isotope Laboratory (ARIEL) and Institute for Advanced Medical Isotopes (IAMI). Demonstrating a commitment to building a diverse and inclusive workforce, he reshaped TRIUMF’s hiring practices and established the laboratory’s Committee on Equity, Diversity, and Inclusion. Bagger is also currently professor of Physics at the University of British Columbia. Prior to his stewardship of TRIUMF, Bagger was the Krieger-Eisenhower professor in the Department of Physics and Astronomy at Johns Hopkins University, where he served as chair of the department. He also served in several administrative positions at the university, including interim senior vice president for academic affairs. He continues to be a research professor at the university.

The APS represents over 55,000 members, including physicists in academia, national laboratories, and industry residing in the United States and throughout the world. The APS is a nonprofit membership organization working to advance and diffuse the knowledge of physics through its outstanding research journals, scientific meetings, and education, outreach, advocacy, and international activities. The APS supports 17 divisions, 9 forums, 10 geographical sections, and 13 smaller topical groups.


The CEO Search Committee was chaired by 2019 APS president David Gross. Members of the committee were 2020 Speaker of the APS Council Andrea Liu, 2011 APS President Barry Barish, 2015–2016 APS Committee on Minorities Chair Nadya Mason, 2016–2018 APS Board Member Nick Bigelow, 2020 APS President Phil Bucksbaum, and 2018 Speaker of the APS Council Tim Gay.
Asymmetric nuclear shapes have been particularly interesting since the discovery of low lying 1− states in between the 2+ and 4+ members of the rotational bands in actinide nuclei. Christy suggested these could arise from “a collective distortion in which the nucleus is pear shaped” [1]. Many years passed before the full range of properties of pear-shaped nuclei were discovered.

Professor Pancholi has written a very comprehensive review of what is known about pear-shaped nuclei, both experimentally and theoretically, and the many different ways of analyzing the data. The energy levels in pear-shaped nuclei form what are called octupole bands. A major strength of the book is the many different ways the data are analyzed to distinguish vibrational from static deformed octupole bands in nuclei.

Chapter one presents the discoveries of the 1− states in actinide nuclei in the 1950s. In the mid 1980s the first high spin spectroscopy in actinide nuclei revealed opposite parity bands with enhanced E1 crossing transitions between them. Soon opposite parity bands were found around 144Ba.

Theoretical descriptions of axially symmetric but reflection asymmetric nuclei gave rise to the simplex quantum number, s, where in even–even nuclei two bands of even–odd spins with opposite parities were expected with similar doublet bands in odd A nuclei.

Chapter 2 begins with a discussion of whether a nucleus is vibrational, transitional, or static deformed. Theoretical calculations predicted quadrupole–octupole deformed shapes around Z = 56, N = 88 and Z = 88, N = 134–136. A very thorough review of actinide data follows. The single particle level energies show a sizable gap for N = 132 and for Z = 88 for stable octupole deformation, with beta3 = 0.08.

Chapter 3 presents high spin behaviors of pear-shaped nuclei. Systematics of actinide nuclei show a minimum in the 1− and 3− levels at N = 134 as predicted by theory. In Ba nuclei these energies decrease to 144Ba. The displacement energies are compared to the stable octupole deformed limit, which is reached in 226Ra, 222,224Th, and 144Ba around spin 8. Then follows detailed comparisons of the experimental data for Ra, Th, and Ba. These comparisons show where the experimental data indicate static and vibrational octupole deformation.

The next section considers odd mass nuclei where parity doublets are found. Again, various ways of looking at the experimental data along with theoretical calculations are major strengths of the book.

Chapter 4 covers the important E1 crossing transitions between the positive and negative parity states compared to the E2 cascade transitions, the B(E1) transition probabilities, the electric dipole moments Do, the 3− states and E(3) moments. The B(E1) transition probabilities are compared to the Weisskopf single particle estimates. These data show which nuclei exhibit octupole correlations. The intrinsic quadrupole moments are extracted and used to obtain the electric dipole moments, Do. The theoretical calculations of Do with both macroscopic and shell corrections reproduce the experimental results for a beta-3 deformation around 0.08. The B(E3,0+–3−) have the strongest values around N = 88–90 and 134–138 as predicted for enhanced octupole deformation. Much larger B(E3) for 222–228Ra and 224–226Th indicate the onset of octupole deformation. In 144–146Ba the data indicate stable octupole deformation above spin 9.

In the final chapter, the experimental findings are carefully summarized for even–even and odd A nuclei. All of the evidence for the regions of octupole vibration and static deformation is reviewed. This chapter is an excellent quick summary of all that is known about octupole vibrational and static deformation. The book is an excellent presentation for scientists who want to study these phenomena in depth.

Reference

Joseph H. Hamilton
Vanderbilt University
In Memoriam: Hubert Grawe (1938–2020)

Hubert Grawe

It is with deep sadness that we have to inform you that Hubert Grawe passed away suddenly on 8 November 2020 at the age of 82. He found his final resting place in Kirchzarten, a small city near Freiburg im Breisgau, which he kept as his homeland ever since he left the university.

Following his studies at the universities of Munich and Freiburg, Hubert received his doctorate in Freiburg at the end of the 1960s under the supervision of Theodor Schmidt. Together with Hermann Schüler, they used atomic spectra to derive evidence for electric quadrupole moments and thus deformation of atomic nuclei. Hubert followed this research line at the Hahn-Meitner-Institut (HMI) in Berlin, where he first worked on combining solid-state physics and nuclear physics to derive precise nuclear moments. The installation of one of the first multi-Ge-detector arrays at a beam-line of the HMI cyclotron provided Hubert with an opportunity for in-beam γ-ray spectroscopy, which he took advantage of with great enthusiasm. Research on nuclei near doubly-magic $^{100}$Sn intensified longstanding personal ties to numerous colleagues in the Nordic countries.

Also at that time, Hubert became particularly interested in the nuclear shell model. This topic became his main research area when he moved to the Gesellschaft für Schwerionenforschung (GSI; Society for Heavy Ion Research) Darmstadt in 1996 to work at the online separator and in nuclear spectroscopy. Among his specialities were not only nuclei with approximately equal proton and neutron number, as near $^{100}$Sn, but also nuclear structure near other double shell-closure nuclei like $^{78}$Ni, $^{132}$Sn, and $^{208}$Pb. His experimental and theoretical work found worldwide recognition, in particular his close collaboration with shell-model theoreticians. Based on his "Shell Model from a Practitioner’s Point of View" [1], he built invaluable bridges between experiment and theory. Moreover, many scholars esteem him as their "shell-model mentor" and will carry on in his spirit.

Hubert was a passionate and tireless physicist, with more than 460 publications, enormous knowledge, and an unerring instinct for physics. After his retirement in 2003, and until his last days, Hubert continued to work on scientific issues with us. Following many of the innumerable train rides from Kirchzarten to either Berlin or Darmstadt for writing articles or gaining new physics insights, the salutation to his colleagues typically was: “You know, sitting on the train this morning with a cup of coffee, I realized…” He was highly appreciated by his colleagues for his constant willingness to discuss, provide assistance, and explain nuclear physics. Hubert had a friendly, open-minded character and was role model for many of us as a great personality and great scientist.

We deeply mourn the death of Hubert Grawe and will keep him in our fondest memories. The loss of such a remarkable man will be felt greatly by all who knew him. In view of Hubert’s many contributions to the field of exotic nuclei, a commemoration event is planned at GSI for 2021.

Reference


Magda Górska
Andrey Blazhev
Jürgen Gerl
Ernst Roeckl
Dirk Rudolph