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Cover Illustration: The Ruder Bošković Institute in Zagreb - see article on page 4.
Diversity in Physics: Diversity Charter

It should not sound strange to anyone if I claim that we still have to work very hard to achieve a “diverse” community in physics. For instance, just take a look around and observe the configuration of any important committee in physics.

One of the problems in deciding how to tackle this is the lack of detailed information on the issue and hard facts and figures.

Within the community, when one talks about “diversity,” it is very often taken as solely a gender issue. Although gender inequality dominates, other important issues loom: ethnicity, nationality, sexuality, and so on.

The question is then: How to proceed? Before embarking on concrete solutions, the first logical action is to carry out a measurement to establish the baseline in order to convince own colleagues that the “problem” exists and it cannot and should not be ignored.

About a year ago, the chairs of the Astro-Particle Physics European Consortium (APPEC), the European Committee for Future Accelerators (ECFA), and the Nuclear Physics European Collaboration Committee (NuPECC) formed a committee composed of Francesca Moglia and Teresa Montaruli (APPEC), Patricia Conde Muíño (ECFA), Jens Jørgen Gaardhøje, Jochen Wambach, and the undersigned (NuPECC), to look at this issue more deeply.

The committee adopted the following (universally accepted) definition of diversity: acknowledgment, respect, and appreciation of the reality that people differ in many ways, visible or invisible, mainly in age, gender, and sexual orientation, national and ethnic origin, civil status and familial situation, religious convictions, political and philosophical opinions, and physical ability.

The major challenge for the committee was to identify indicators to be used in measurements. It is imperative to make sure that any questions and questionnaires cannot be correlated with individual persons, violating the privacy of participants. In addition, we did not want to have a very lengthy questionnaire that would reduce the participation level of scientists.

What we called “monitorable” variables are: gender, tenure diversity (career level), age diversity (age groups), country of employment, and citizenship. We are aware that making this selection excludes a few other important indicators (sexual orientation, physical abilities, race/ethnicity, etc.) but due to the aforementioned concerns, we wanted to limit the study to the five we chose. We think that a questionnaire will clarify the situation on many aspects, such as positions of responsibility as a function of gender, nationality, country of employment, age, and career level, or (assigned/invited) talks at conferences as a function of the same parameters.

The next important discussion point was with whom one should start to make the studies. We perform our study on focus groups (such as APPEC, ECFA, and NuPECC), on organizations and conferences in which these communities participate (with a minimum number of participants, depending on the field), and on large collaborations (again with a minimum number of around 50 participants).

The Charter (http://ecfa.web.cern.ch/content/diversity-charter) has now been approved by the general assemblies of APPEC, ECFA, and NuPECC and the questionnaire was already put to its first test during the JENAS conference in October 2019. The outcome of the study clearly shows on which points some discussions should take place (such as female colleagues getting less permanent positions compared to their male counterparts, and at a later age).

The committee will work on analyzing the data from conferences and so on the coming two years and try to come up with a summary and perhaps recommendations.

Nasser Kalantar-Nayestanaki
KVI-CART Groningen

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Ruđer Bošković Institute Accelerator Facility

History
The Ruđer Bošković Institute Accelerator Facility (RBI–AF) consists of two accelerators: a 6.0 MV EN Tandem Van de Graaff accelerator and a 1.0 MV Tandetron accelerator. The facility is operated within the Division of Experimental Physics of the RBI, which is the largest scientific institute in sciences and in marine and environmental research in Croatia.

The RBI–AF was established in 1987 when the 6.0 MV EN Tandem Van de Graaff accelerator was installed after donation and shipment from Rice University, Texas, USA. In the beginning, only protons and light ions with terminal voltages of up to 3 MV were used, mainly for two ion beam analysis (IBA) techniques, proton induced X-ray emission (PIXE), and Rutherford backscattering spectrometry (RBS). The first ion microprobe, based on an Oxford Microbeams Ltd. magnetic quadrupole doublet, was installed in 1991. Together with an early development of μ-PIXE and μ-RBS, the laboratory pioneered the development of ion beam induced charge (IBIC), a technique that is today one of the most utilized accelerator-based techniques for imaging charge transport properties in radiation detectors and other electronic devices [1].

The 1.0 MV Tandetron accelerator supplied by High Voltage Engineering Europa B.V. and funded by the International Atomic Energy Agency (IAEA) and the Ministry of Science of Croatia was commissioned in 2005.

Today
Most of the beam-lines were constructed or upgraded after Tandetron installation. The layout of the RBI–AF displaying both accelerators and all beam-lines is shown in Figure 1. Each accelerator is equipped with two negative ion sources, the EN Tandem with an RF source (S1) and a multi-cathode sputtering ion source (S2). The Tandetron has a duoplasmatron (S3) and sputtering ion source (S4). Eight out of the nine beam-lines are dedicated to ion beam physics and applications and are managed by scientists from the Laboratory for Ion Beam Interactions (LIBI), while the ninth is dedicated to low energy nuclear physics experiments and is managed by scientists from the Laboratory for Nuclear Physics. LIBI researchers are focused on basic and interdisciplinary research related to the ion–matter interactions, with a continuous effort to develop new experimental arrangements for the characterization and modification of materials.

Experimental stations E1 and E2 can only use ions delivered by the 1 MV Tandetron. The E1 is a standard multipurpose scattering chamber designed in-house and developed under the IAEA TC project during the 2008–2010 funding cycle. It is equipped with two PIXE detectors—SDD and Si(Li)—to cover a broad range of elements. Other IBA techniques can be applied simultaneously with PIXE, such as RBS for light element analysis and/or foil elastic recoil detection analysis (ERDA) or proton elastic scattering analysis (PESA) placed at 45° for H analysis. E2 delivers an external proton beam through the thin Al foil for in-air PIXE analysis of samples that are not suited for analysis in a vacuum, either due to their size or sensitivity. The existence of two accelerators opened new and unique application possibilities, and RBI–AF is currently one of about 10 laboratories in the world with the ability to investigate materials by simultaneous irradiation with ion beams from two accelerators at two dual-beam end stations (E3 and E4). E3 is still under construction and, when finished, is planned to have microbeam focusing for both of the beams. This end station already offers the possibility of irradiation with one microbeam (from Tandetron), while the other one (from EN Tandem) is collimated. The completed microprobe is based on the in-house-designed quadrupole triplet, while the other microprobe that is under construction will be based on the electrostatic quadruplet lens system (suitable for heavy ions). When finished, dual microprobe will be the only of its kind in the world with the ability to test the irradiation effects in materials on the micrometer scale. Additionally, it would be possible to use one microbeam as a damaging beam and another as a probe to measure ion beam–induced changes in the materials (e.g., by PIXE or RBS channeling), or to test the response of electronic systems by IBIC. The positions of the experimental beam-lines (from E3 to E9) in the large experimental hall can be seen in Figure 2.

The E4 end station, also referred to as the dual ion beam for fusion materials research (DiFU), shown in Figure 3 was developed as a part of the H2020 EUROfusion project grant no. 633053 and as an upgrade of the irradiation chamber designed and constructed through the FP7 REGPOT project “Particle Detectors.” It enables testing the response of materials that are important for future fusion reac-
tors using simulation of fusion environment by dual ion beam irradiation; that is, by self-ions (heavy ions) simultaneously with He ions. The irradiation of samples can be performed by electrostatically scanning ion beams with a high scanning frequency. The energy of ion beams at the target can be adjusted either by a subsequent change of ion beam energy from the accelerator or by using Al-foil-based ion beam degraders that rotate in front of the sample and enable the production of a homogeneous damage depth profile. The heating and cooling of the sample is possible, as well as the installation of additional equipment upon the user’s request [2].

The E5 end station is composed of an in-house-built time-of-flight elastic recoil detection analysis (TOF-ERDA) spectrometer. It provides a depth-profiling analysis of all elements present in the first 500 nm of the sample, with a nanometer depth resolution. Hydrogen and its isotopes can be quantified and depth profiled simultaneously with all other elements, which is important for fusion research (D retention). The semiconductor detector that was used for detecting energies of recoiled ions was recently replaced by an in-house-built gas ionization chamber that is resistive to ion-beam-induced damage [3]. The TOF-ERDA spectrometer with the gas detector is shown in Figure 4a. The use of the gas detector improved both stability and mass resolution to M/ΔM = 40.

The TOF-ERDA spectrum of a thin LSCO film measured by 20 MeV $^{127}$I$^{6+}$ ions is shown in Figure 4b. By extending the E5 beam-line, the new end station E6, a capillary microprobe, was recently built for 2-D molecular imaging using time-of-flight secondary ion mass spectrometry with MeV ions (MeV SIMS). This new setup should overcome some of the limitations of our first linear TOF MeV SIMS setup, installed in 2013 at the heavy ion microprobe (E9), regarding maximum sample size ($\approx 1\times1$ mm$^2$) and ions that can be used. Instead of a complex and expensive system of focusing lenses, ions are collimated to the micron dimension with a conical glass capillary. Therefore, heavier ions such as I or Au with energies up to 30 MeV can be used while secondary molecular ion yield strongly depends on the electronic stopping power. Furthermore, the mass resolution of the new setup by using reflectron-type TOF analyzer is nearly 2,500 at 576 Da.

The E7 end station is mainly used for channeling experiments using RBS and PIXE [4]. It is equipped with a goniometer that allows movement with five degrees of freedom, and it has an angular accuracy of 0.01°. A particle detector at 160° or SDD X-ray detector at 150° is used for recording the EBS

Figure 1. Layout of the RBI–AF.

Figure 2. Experimental beam-lines (from E3 to E9) in the large experimental hall.
or PIXE channeling spectra, respectively. The end station is equipped with an electron beam heater for heating the samples up to 600°C, allowing in situ measurements as well. The PIXE channeling spectrum of N:SiC, showing the Si Kα X-ray map obtained at RT, 0.1 sec/pixel is displayed in Figure 5.

The E8 is dedicated to nuclear structure and nuclear reaction research and is based on a large silicon detector array. It was constructed in 1992 for measurements with 1-D position-sensitive detectors and solid targets and upgraded in 2010 and 2013 for measurements with gas targets and large area double-sided silicon strip detectors. The upgrades were funded by two FP7 REGPOT projects (CLUNA and Particle Detectors). The current experimental setup consists of up to four silicon detector telescopes assembled from the thin single side and the thick double-side strip detectors and readout electronics and a virtual matrix encryption (VME)-based data acquisition system for processing up to 192 detector signals.

The first research topic is focused on cluster and molecular structure in neutron-rich isotopes of beryllium, boron, and carbon. Measurement of the \( ^7\text{Li} + ^7\text{Li} \rightarrow \alpha + \alpha + ^6\text{He} \) reaction provided the first strong indication for the molecular \( \alpha + 2n + \alpha \) structure in \(^{10}\text{Be} \) [5]. This result initiated a series of experiments at accelerator facilities worldwide that confirmed this exotic structural mode in light nuclei. Another successful study was the measurement of \(^9\text{Be} + ^4\text{He} \) resonant scattering, which confirmed strong \(^9\text{Be} + ^4\text{He} \) clustering in the \(^{13}\text{C} \) nucleus.

The second research topic includes measurements of the three-body quasi-free reactions as a tool for the indirect study of nuclear reactions in astrophysical environments based on the Trojan Horse Method. This method enables the determination of the bare astrophysical factor for two-body nuclear reactions at very low energies typical for astrophysical sites through measurements of the three-body reaction in quasi-free conditions at typical beam energies for small accelerators [6].

The heavy-ion microprobe E9 enable the application of almost all available IBA techniques: PIXE, RBS, ERDA, nuclear reaction analysis (NRA), IBIC, scanning transmission ion microscopy (STIM), MeV SIMS, ion luminescence (IL), and high resolution-PIXE (HR-PIXE). The beams that can be applied are protons (0.4 to 8 MeV) and most other heavier ions up to the maximum mE/q² ratio of 14 MeV. Depending on the application and the ion magnetic rigidity, a doublet or triplet of the quadrupole focusing lenses is used. In the high current mode, which is needed for IBA, PIXE and/or RBS are operated by protons or He. Concerning light elements, the microprobe 3-D analysis of hydrogen or carbon is achieved using coincident scattering [7]. Recently, in the framework of the EUROfusion project, \(^3\text{He} \) ion microbeam NRA was used to determine the composition of dust particles from the Joint European Torus during operation with the ITER-like wall [8].

Typical beam lateral resolution in the high current mode is around 1 μm, while in the most favorable conditions of the low current mode, it can be 250 nm. In the low current mode, ion beam currents are in the fA range for STIM and IBIC. More than 100 papers using IBIC at the RBI microprobe have been published so far. However, the full utilization of the IBIC was fostered mostly through several recent European Union projects dealing with the development of radiation detectors (the FP7 project Particle detectors, H2020 project PaRaDe-SEC, and H2020 project AIDA 2020). Particularly recognized applications of IBIC were those related to controversies in the radiation hardness of diamond detectors, charge multiplication in diamond membranes [9], and
investigations of charge collection in radiation hard 3-D detector structures. Figure 6 shows diamond irradiation at 750 °C in the heavy ion microprobe.

One of the most interesting and unique applications using focused ion beams is the downsized wavelength dispersive X-ray (WDX) spectrometer for HR PIXE studies of the chemical effects on X-ray spectra. The spectrometer is based on a very simple design with a flat diffraction crystal and a position-sensitive CCD X-ray detector that, in combination with a focused ion beam, can be applied for the analysis of micrometer-size samples. The spectrometer is currently equipped with diffraction crystals, which enable measurements of X-rays in the energy range from 1.2 to 8.4 keV, with the energy resolution E/ΔE(FWHM) 1850 on Al Kα and 1580 on Si Kα achieved with 2 MeV protons. With this energy resolution, secondary effects in the K X-ray spectra of light, the L-shell spectra of medium, and the M-shell spectra of heavy elements can be studied [10]. Figure 7 shows the downsized WDX spectrometer for HR PIXE studies, which is attached directly after the main microbeam chamber.

Several years ago, MeV SIMS was introduced at the RBI heavy ion microprobe. This mass spectrometry technique provides 2-D molecular imaging of organic samples using linear TOF spectrometer and MeV ions for excitation. So far, this technique has been successfully applied for the molecular imaging of single cells at the submicron level [11], for the 2-D imaging of synthetic organic pigments, and for the determination of the deposition order of different writing tools for forensic applications [12].

The tradition of developing data acquisition systems (DAQ) in the LIBI started more than 25 years ago. The multidisciplinary nature of the experiments, especially those performed using focused ion beams, requires the recording of different multiparameter spectra and information about the beam. This need boosted the development of flexible, fast, and easy-to-use DAQ systems. The first-generation DAQ system was based on a FAST MPA/PC adapter card and a programmable external ADC bus-box that supported up to 8 input ports connected to the MPA/PC card and ADCs, position processors, or any other compatible devices. Later, a DAQ system based on a Xilinx Spartan-IIE FPGA and a Texas Instruments TMS320VC33 digital signal processor was developed. The last version of the DAQ system is based on the Xilinx Virtex 6 ML605.
laboratory portrait

Figure 6. Irradiation of diamond at 750 °C in the heavy ion microprobe chamber.

Figure 7. Downsized WDX spectrometer for HR PIXE.

development platform, which consists of 1 GB of onboard DDR3 RAM, ethernet connectivity, and two FPGA Mezzanine Card connectors that can be easily reconfigured for different applications. In addition to PHA, TDC measurements were performed with a chopped beam achieving a time resolution of 1.67 ns [13].

Because RBI–AF is the largest research infrastructure site in Croatia, external users consume a significant fraction of the beam time, mostly using standard IBA techniques and increasingly material irradiation and implantation techniques. Access was provided through an agreement with the IAEA since 1997 and during the period from 2011 to 2013 it was provided through the FP7 project SPIRIT. Presently, RBI–AF provides access in the framework of the Horizon 2020 project RADIATE to the most developed techniques for materials analysis and modification based on ion beams to researchers from academia and industry. Additionally, since 2017, RBI–AF has been a member of the regional research infrastructure network CERIC-ERIC. The RBI–AF currently provides approximately 2,500 hours of beam time per year. The primary task of the accelerator facility is to serve researchers within national research projects. These activities account for more than 50% of the total accelerator beam time. Concerning international collaborations, for which the share of the total beam time increased from 14% in 2007 to almost 40% in 2017, the longest-lasting collaboration is with the IAEA (since 1997). Each year, RBI hosts more than 50 foreign researchers who visit the accelerator facility for hands-on experiments. More than 5% of the total beam time is dedicated to commercial services.

To maintain international visibility and to enhance the use of ion beam technology as a possible key enabling technology within the smart specialization strategy for Croatia, a series of investments are planned, two most important through the ERDF projects: Centre of Excellence for Advanced Materials and Sensing Devices and Open Scientific Infrastructural Platforms for Innovative Applications in the Economy and Society. These two projects aim to increase the reliability and competitiveness of the accelerator facility by investments of more than 5 Mio. €in the next five years, including the planned purchase of a new 5.0 MV tandem accelerator.

Research Highlights

Molecular Imaging of Single Cells

Molecular composition inside an individual cell at the submicron level is important to better understand the biochemical processes governing the cell. For that purpose, a MeV SIMS setup with a continuous primary ion beam was used, with START triggered using a signal from the PIN diode placed behind the sample (CaCo-2 cells mounted on 100-nm-thick Si₃N₄).

This allowed us to work in a low current mode where primary 9 MeV O⁺ ions were focused to submicron dimensions, resulting in 2-D distributions of Na⁺, K⁺, and lipid fragments inside the single cells [11]. Additionally, a STIM image that is collected simultaneously can be used for cell localization without using any additional markers, while providing information about the density distribution inside the cell.

Diamond Thin Film Membrane

A 6-micron-thick self-supported diamond membrane was used twofold, as a transmission single ion detector and as a vacuum/air interface. The detector was produced from a scCVD diamond on which Al contacts were evaporated. It was first fully characterized in a vacuum and was found to have an excellent signal to noise ratio and a very high efficiency to detect ions (close to 100%, even for low linear energy transfer [LET] protons). The concept has several advantages compared to conventional configurations based on secondary electron detectors or scintillators. First, the diamond is installed as a vacuum window so there is no need for additional vacuum foil. Second, the detection efficiency for light ions is significantly better compared to the cases for which secondary electron lights have to be detected from the standard exit foil. Finally, the operation is much simpler because there is no need to work in darkness, as is the
case when photons from the standard exit foil are detected [14].

**Fundamental Parameters for Analysis of PIXE–XRF Spectra from Mars**

In collaboration with Prof. J. L. Campbell from the University of Guelph, the influence of multiple ionization satellites on the analysis of PIXE–X-ray fluorescence (XRF) spectra obtained by the alpha particle X-ray spectrometers (APXS) mounted on several Mars rovers. The X-ray spectra acquired on Mars by SDD are obtained by PIXE and X-ray fluorescence mechanisms through the exposure of Mars soil and rocks to a combined primary radiation of 5 MeV alphas and plutonium L X-rays. The presence of multiple ionization (MI) satellites generated by alpha particle excitation in combination with SDD instrumental nonlinearity affects the quality of the nonlinear least-squares fits for the APXS spectra. Therefore, a HR PIXE spectrometer was used to measure the MI X-ray satellites of low Z elements in order to improve the PIXE analysis accuracy. So far, K-shell MI spectra of magnesium, aluminium, and silicon excited by alpha particles PIXE at He energies from 3 to 5 MeV have been measured [15].

**Acknowledgments**

The author thanks M. Jakšić, N. Soić, S. Fazinić, Z. Siketić, and T. Tadić for their contributions to this article. LIBI members acknowledge the longstanding funding and support of the IAEA, the Ministry of Science and Education of Republic of Croatia, the Croatian Science Foundation, and the European Union, as well as donations from Rice, Oxford, Heidelberg, Uppsala, and Linz Universities.

**References**

Global Polarization Effect in the Extremely Rapidly Rotating QGP in HIC

Zuo-Tang Liang, Michael Annan Lisa, and Xin-Nian Wang

1Key Laboratory of Particle Physics and Particle Irradiation (MOE), Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, Shandong 266237, China
2Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA
3Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan, 430079, China
4Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

Introduction: QGP as a Perfect Fluid

Recently, the global polarization of Λ and Λ– hyperons in heavy-ion collisions (HIC) has been observed [1] by the STAR Collaboration at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory (BNL). The discovery confirms the theoretical prediction [2] made more than 10 years ago and indicates that the quark gluon plasma (QGP) produced in HIC possesses a vorticity as high as $10^{21}$ s$^{-1}$, much higher than any other fluid observed in nature. This opens a new window to study properties of QGP and a new direction in high energy heavy ion physics.

QGP is an extraordinary state of matter under strong interaction. As early as the 1970s, T. D. Lee and G. C. Wick suggested that [3] “by distributing high energy or high nucleon density over a relatively large volume,” one could temporarily restore broken symmetries of the physical vacuum and possibly create a new state of dense nuclear matter. At the same time, it was realized that the asymptotic freedom of quantum chromodynamics implies the existence of an ultra-dense form of matter where all known hadrons are expected to dissolve into a plasma of their elementary constituents, the deconfined quarks and the gluons.

The QGP state is thought to have existed in the early universe after the Big Bang [4]. The transition from QGP to hadronic matter is believed to be one of several transitions occurring during the first few microseconds, when the temperature was of the order of hundreds of MeV ($\sim 10^{13}$ K). It was pointed out that, in a laboratory, conditions required to create QGP could be achieved in the laboratory by colliding two heavy nuclei at high energies (see Figure 1). Since then, QGP has been the focus of an extensive experimental program at the Super Proton Synchrotron and Large Hadron Collider (LHC) facilities at CERN, as well as RHIC at BNL [5].

The QGP observed in HIC has a number of remarkable properties manifested in azimuthal elliptical flow, jet quenching, and other phenomena [6]. It is also opaque to fast partons that carry color charge. These phenomena indicate that the

Figure 1. Illustration of the evolution of a heavy ion collision. The partonic matter system is found to be in the QGP state.
QGP is a fluid with minimal viscosity, often called the “perfect fluid” [7]. A HIC event at RHIC is illustrated in Figure 2.

As we discuss below, the study of polarization in HIC probes the fine rotational substructure of this perfect fluid.

**Global Orbital Angular Momenta of QGP in HIC**

Spin, as a fundamental degree of freedom of elementary particles, plays a very important role in modern physics and often brings us surprises. There are many well-known examples in the field of high-energy physics, such as the so-called proton spin crisis [8] triggered by measurements on spin-dependent structure functions in deeply inelastic lepton–nucleon scattering, the single transverse spin left–right asymmetry in inclusive hadron production in hadron–hadron collisions [9], as well as the transverse hyperon polarization with respect to the production plane in unpolarized proton–proton and proton–nucleus collisions. Such studies are among the most active in strong interaction physics.

The role of spin in HIC was largely ignored until it was realized [2] that the huge orbital angular momentum in these collisions may couple to spin degrees of freedom of the produced quarks. Exploring this phenomenon could provide an entirely new probe of the QGP, as well as studying the exchange of orbital and spin angular momentum under the most extreme conditions.

The reaction plane and the geometry of a HIC as illustrated in Figure 3 can be further clarified in Figure 4. In the upper left panel, a nucleus (denoted the “projectile”) travels in the +z-direction, colliding with the “target” traveling in the −z-direction. The impact parameter, \( b \), is the transverse component of the vector pointing from the target to the projectile. We take \( b \) to define the +x-direction. The normal of the reaction plane is given by \( n \propto p \times b \) is along the y-direction.
The orbital angular momentum of the QGP, \( L_y \), also known as the global angular momentum, in a noncentral HIC has been estimated in Refs. [2, 10] using a hard sphere or Wood-Saxon distribution of the nuclear matter in a nucleus. The results are shown in Figure 5. Here we see that the global orbital angular momentum of the QGP formed in HIC at RHIC can be as large as \( 10^5 \hbar \).

This global angular momentum of the partonic system can be manifested in the finite transverse gradient of the average longitudinal momentum \( p_z \) per produced parton along the \( x \)-direction. From the transverse gradient \( dp_z/dx \), Ref. [10] has also made an estimation of the so-called local orbital angular momentum for two partons in QGP with a transverse separation \( \Delta x \). The typical magnitude \( l_0 \sim (\Delta x)^2 dp_z/dx \) in Au + Au collisions at \( \sqrt{s} = 200 \) AGeV is \( l_0 \sim 1.7 \) for \( \Delta x = 1 \) fm and is indeed sizable.

In more realistic hydrodynamic simulations of noncentral collisions [11], local vorticities are generated through collected flow in a homogenous fluid, as shown in Figure 6. In the transverse plane of a noncentral Au + Au collision, the pattern of the local vorticity has a ring structure. The net sum of the local vorticity is non-zero in the direction perpendicular to the reaction plane caused by the global angular momentum transferred to the fluid system.

### Spin-Orbital Coupling in a Relativistic Quantum System

It has been known for a long time that spin-orbital coupling is an intrinsic property of a relativistic fermionic quantum system. This can be seen most clearly from the Dirac equation. Even for a free Dirac particle, the Hamiltonian, \( \hat{H} = \alpha \cdot p + \beta m \), does not commute with the orbital angular momentum \( \hat{L} \) and the spin operator \( \hat{S} = \Sigma / 2 \) separately, but commutes with the total angular momentum \( \hat{J} = \hat{L} + \hat{S} \). This tells us clearly that the spin and the orbital angular momentum coupled to each other and should be able to transfer from one to another in a relativistic fermionic quantum system. The strength of the spin-orbital coupling should be dependent on the strength of the interaction in the system considered. It should be different for a strongly interacting system from that for an electromagnetically interacting system.

There are many well-known effects due to spin-orbital coupling in a system with electromagnetic interactions. The textbook example is the fine structure of atomic spectra. It also plays a very important role in modern spintronics in condensed matter physics where spin transport in the electromagnetically interacting system is studied.

The transfer of spin polarization (magnetization) and orbital angular momentum (rotation) in electromagnetically interacting systems was discovered just over a century ago [12,13]. Barnett found that rotation can cause magnetization at an object, while Einstein and de Haas showed that a magnetic field may induce rotation.

In systems with strong interactions, spin-orbital coupling also leads to many distinguished effects. One famous example is the nuclear shell model developed by Mayer and Jensen [14], where spin-orbit coupling plays a crucial role to produce the magic numbers of atomic nuclei. Currently, in the frontier of high-energy spin physics, the orbital angular momentum is argued not only to contribute to the proton spin due to spin-orbital interactions but also can be responsible for the single-spin left–
right asymmetries and other single-spin effects observed experimentally. The study of the role played by the orbital angular momentum is one of the core issues currently in high-energy spin physics [8].

Globally Polarized QGP in HIC

It was realized that spin-orbit coupling in a strongly interacting QGP with large orbital angular momentum can lead to polarization of quarks and anti-quarks in noncentral heavy-ion collisions.

The theoretical calculations [2] based on pQCD in the hot nuclear medium show that a quark can acquire a reasonably large polarization in the same direction as the initial orbital angular momentum after one collision with another parton in a fluid with nonvanishing local angular momentum or vorticity. This led to the prediction that quarks and anti-quarks in QGP created in noncentral HICs are polarized in the direction of the global angular momentum of the initial colliding system.

As illustrated in Figure 7, such a polarization [2] is quite different from other cases in high-energy physics, such as the longitudinal or the transverse polarization. The longitudinal polarization refers to the helicity or the polarization in the direction of the momentum, whereas the transverse polarization refers to directions perpendicular to the momentum, either in the production plane or along the normal of the production plane. These directions are all defined by the momentum of the individual particle. In contrast, the polarization discussed here refers to the normal of the reaction plane of an event. It is a fixed direction for one collision event and is independent of the direction of any particular hadron. Hence, in Ref. [2], this polarization was given a new name—the global polarization, and the QGP was referred to the globally polarized QGP in noncentral HIC.

The global polarization of QGP can manifest itself in different observables. The most obvious one should be the global polarization of hadrons produced in the hadronization of the QGP. In Ref. [2], global polarizations of produced hyperons are estimated. The spin alignment of vector mesons (hadrons with spin-1) has also been calculated [14]. Many other observables and calculations based on different approaches have also been discussed in the literature. See, for example, a summary by Qun Wang in Quark Matter [16].

STAR Experiments and the Vorticity of QGP

These novel predictions on the global polarization attracted immediate attention, both experimentally and theoretically. A new preprint [17] only three days after the first prediction [2] attempted to extend the idea to other reactions. Experimentalists in the STAR Collaboration had also started measurements shortly afterward.

Both hyperon polarization and vector meson spin alignment can be measured via the angular distribution of decay products. For hyperon polarization, the polarization is measured by the so-called self-spin analyzing weak decay. For example, for Λ hyperon, this can be measured by studying the weak decay $\Lambda \rightarrow p\pi^-$,

$$\frac{dN}{d\Omega} = \frac{N}{4\pi} \left(1 + aP_{\Lambda}\cos\theta\right)$$

Figure 7. Illustration of the global polarization effect in noncentral heavy-ion collisions.

Figure 8. A sketch of a heavy ion collision in the STAR detector system. The reaction plane was determined by measuring the sideward deflection of the forward- and backward-going fragments and particles in the beam–beam counter detectors. Taken from Ref. [1].
θ is the decay angle of the proton with respect to the polarization direction of Λ in its rest frame, α is a known constant that is called a decay parameter, and $P_\Lambda$ is the magnitude of the polarization.

Measurements of global Λ hyperon polarization and $K^*$ and $\phi$ vector meson spin alignments were attempted soon after the publication of the theoretical predictions [2, 14]. Studies of both aspects have advantages and disadvantages. Hyperon polarization is a linear effect where the polarization for directly produced Λ is equal to that of quarks. The spin alignment of vector meson is a quadratic effect proportional to the square of quark polarization. Hence, the magnitude of effects of vector meson spin alignment should be much smaller than that of hyperon polarization. However, to measure the polarization of hyperon, one has to determine the direction of the normal of the reaction plane, which is not needed for measurements of vector meson spin alignments. Also, the feed down effects due to decay contributions to vector mesons are negligible, but not for Λ hyperons.

Although there were some promising indications, the results obtained in the early measurements [18, 19] by the STAR Collaboration both on Λ hyperon polarizations and vector meson spin alignments were consistent with zero within the large errors. STAR measurements continued during the beam energy scan (BES) experiments and positive results were obtained with improved accuracies [1].

A sketch of a HIC in the STAR detector system is given in Figure 8, where the reaction plane was determined by measuring the sideward deflection of the forward- and backward-going fragments and particles in the beam-beam counter detectors.

Figure 9 shows the results obtained by the STAR Collaboration for the global polarization of Λ and $\bar{\Lambda}$ as functions of the collision energy. The obtained value averaged over energy is $1.08 \pm 0.15$ (stat) $\pm 0.11$ (sys) percent and $1.38 \pm 0.30$ (stat) $\pm 0.13$ (sys) percent for Λ and $\bar{\Lambda}$, respectively.

If QGP is in equilibrium and we can treat it as a vortical ideal fluid consisting of quarks and anti-quarks, the global polarization of Λ hyperon is directly related to the vorticity of the system [20]. The fluid vorticity may be estimated from the data using the relation given in the hydro-dynamic model, and it leads to a vorticity $\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$. This far surpasses the vorticity of all other known fluids (see Figure 10). It was therefore concluded that QGP created in HIC is the most vortical fluid in nature yet observed.

**The Outlook**

The early theoretical prediction [2] and discovery of global spin polarization in noncentral HIC by the STAR Collaboration [1] open a new window to study properties of QGP and a new direction in high energy heavy ion physics. With much higher statistics, the STAR Collaboration has repeated measurements [21] in Au + Au collisions at 200 AGeV and obtained positive results with much higher accuracies. The ALICE Collaboration at the LHC has also carried out similar measurements in Pb–Pb collisions [22]. Other efforts on measurements of vector meson spin alignments have also been attempted. The STAR Collaboration has just finished major detector upgrades and started the beam energy scan experiments at phase II (BES II). The successful detector upgrade with improved inner time projection chamber and event plane detector will be crucial to the measurements of global hadron polarizations. The STAR BES II will provide an excellent opportunity to study the global polarization in HIC and we expect new results with higher accuracies in the coming years.

There are also many exciting studies in this connection, such as different approaches to calculate the global polarizations, other measurable effects on global polarizations, and also other effects in connection with the huge orbital angular momenta of the colliding systems in HIC. Interested readers are referred to recent overviews, such as Ref. [16].
In addition to vorticity and rotation, these polarization studies may provide a unique probe of the huge magnetic fields that are expected in HIC. The relativistic charged nuclei should produce fields on order $10^{14}$–$10^{16}$ Tesla, at least instantaneously. The superconducting nature of the QGP may extend the lifetime of this field as the system evolves. While vortical or spin-orbit coupling tends to align all spins in the same direction, magnetic coupling can produce a “fine structure” to the coupling systematics [18]. In particular, a strong magnetic field would enhance the polarization of $\Lambda$ and slightly suppress that of $\bar{\Lambda}$. Indeed, the data in Figure 9 suggest just such a fine-structure pattern, and if error bars are ignored, would indicate $B \sim 10^{14}$ T, higher than any other magnetic field in the universe (see Figure 11). However, much smaller uncertainties—available with the new BES-II data—will be needed to resolve the issue.

Acknowledgments
We thank in particular the STAR Collaboration for providing the excellent experimental environments and for the standing efforts in carrying the measurements in this direction. This work was supported in part by the National...
Natural Science Foundation of China (Nos. 11890713, 11675092, 1186131009, 11935007, and 11890714), by the U.S. National Science Foundation award 1614835, and DOE under Contract No. DE-AC02- 05CH11231.

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Introduction

First, I should define what is meant by a precision prediction: A prediction is considered precise if it has a small (relative) theoretical uncertainty. This, however, does not imply that it agrees with an experiment. Also, the mentioned small uncertainty can be best quantified if we have an underlying counting rule based on some small parameter. Needless to say, a prediction without uncertainty makes little sense. Finally, in what follows I will mostly consider the interplay of precision predictions with the corresponding precise experiments.

To set the stage, let me consider two by now classical examples. The first concerns the masses of the top quark and the Higgs boson, which were already known within certain ranges before the direct measurements. The underlying idea is that virtual heavy particles can leave traces in processes involving lighter ones, such as the top quark in loops in electron–positron collisions at the large electron–positron collider (LEP) producing, for example, a \( bb \) pair that further hadronizes into jets (see Figure 1).

Combining such precision measurements with extremely precise higher-loop electroweak calculations, the top quark mass was known to be in the range between 150 and 200 GeV (see, e.g., Ref. [1]), completely consistent with the direct measurement of 175 GeV at the Tevatron in 1995. Similarly, a window for the Higgs boson mass was set by radiative corrections between 114 and 156 GeV, again consistent with the direct measurement of 125 GeV at CERN in 2012. The second well-known example is the so-called Hulse-Taylor pulsar, which has led to fine tests of general relativity (GR). In fact, GR predicts the slowing down of the pulsar period \( P_0 \) due to the radiation of gravitational waves. In their famous paper from 1979, Taylor, Fowler, and McCulloch state that measurements of relativistic effects in the orbit of this binary pulsar lead to a quantitative confirmation of the existence of gravitational radiation at the level predicted by GR [2]. Over four decades, this system has become a true precision test of GR, clearly giving evidence to the existence of gravitational waves as predicted by GR [3]. Gravitational waves were finally detected directly by LIGO/VIRGO in 2015. In what follows, I discuss a few selected recent results.

From Schwinger’s Tombstone to Ultrahigh Precision

Dirac made the famous prediction that the Landé factor of an electron is \( g = 2 \), which was challenged by experiments in the late 1940s. Schwinger, one of the fathers of quantum electrodynamics (QED), did the first calculation of the anomalous magnetic moment of the electron, \( a_e = (g_e - 2)/2 = \alpha/(2\pi) \approx 1.1 \times 10^{-3} \), with \( \alpha \) the fine-structure constant, \( \alpha = 1/137.03599 \ldots \) [4]. This was the dawn of the precision era and this textbook result is engraved on Schwinger’s tombstone in Pasadena. In fact, the anomalous magnetic moment is the most precise prediction of the tremendously successful Standard Model (SM) of the strong, electromagnetic and weak interactions, \( a_e = a_e^{\text{(QED)}} + a_e^{\text{(weak)}} + a_e^{\text{(strong)}} \).

The QED part splits into various pieces depending on the lepton mass ratios, \( a_e^{\text{(QED)}} = A_1 + A_2 (m_e/m_\mu) + A_2 (m_e/m_\tau) + A_3 (m_e/m_\mu, m_e/m_\tau) \), in terms of the electron, the muon, and the tau mass. To achieve sub-ppb precision as in an experiment, we must know \( A_1 \) to the tenth order, as \( (\alpha/\pi)^{10} = 0.07 \times 10^{-12} \). The completed and correct calculation of the 12,762 tenth-order diagrams was reported by Kinoshita and collaborators in 2018 [5]. The SM prediction reads \( a_e^{\text{(QED)}} = 1159652182.037(11)(12)(229) \times 10^{-12} \), where the first error is due to QED, the second one stems from quantum chromodynamics (QCD), and the last one from the uncertainty in \( \alpha \), measured from the Rydberg levels in atomic Cs [6]. The weak contribution is too small to feature here. This result agrees remarkably well with the so far most precise measurement, \( a_e^{\text{(exp)}} = 1159652181.73(28) \times 10^{-12} \) [7]. One notices a small tension, but before speculating about a possible contribution from physics beyond the SM, the planned improved measurements of the Rydberg constant and of the anomalous magnetic moment of the electron should be performed (see, e.g., Ref. [8]).
The effects of heavy mass particles are enhanced by \((m_\mu/m_e)^2 \sim 43,000\) in the muon (g-2). Here, there is a tension between the most precise experiment and the theory (see, e.g., Ref. [9]), but to really draw firm conclusions, one is eagerly awaiting on the one hand the result of the new Fermilab measurement and on the other hand an improved calculation of the theoretical uncertainty for the hadronic light-by-light scattering contribution based on dispersion theory [10].

**Precision Sigma-Term Physics**

Massless classical QCD is invariant under scale transformations (dilatations), \(r \rightarrow \lambda r\), with \(\lambda\) a real number. This scale invariance is broken by quantization, the well-known dimensional transmutation leads to the scale \(\Lambda_{\text{QCD}} = 250\) MeV, that can, for example, be inferred from the running of the strong coupling constant as well as the nonvanishing of the trace of the QCD energy-momentum tensor, \(\Theta_{\mu}^{\mu}\). This so-called *trace anomaly* leads to the generation of hadron masses. For the proton \(|p\rangle\), this reads (neglecting a small anomalous dimension term) [11]:

\[
mp = <p|\Theta_{\mu}^{\mu}|p> = <p|\beta_{\text{QCD}}(g)G_{\mu\nu}G_{\rho\sigma}^{\mu\nu} + m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s|p>,
\]

with \(\beta_{\text{QCD}}\) the QCD \(\beta\)-function, \(g\) the strong coupling constant, \(G_{\mu\nu}^{a}\) the gluon field strength tensor, and \(m_f\) the mass of the quark with flavor \(f\), \(f = u,d,s\). The first term in Eq. (1) is pure gluon field energy and the last three terms give the contribution from the Higgs boson to the proton mass. The term proportional to the light up and down (strange) quark masses is called the pion-nucleon (strangeness) sigma-term, \(\sigma_{\pi N}\) and \(\sigma_s\), respectively. These sigma-terms play a much larger role than just giving a part of the proton mass; they parameterize the scalar couplings of the nucleon, which are of utmost importance for direct dark matter detection as well as muon to electron conversion in nuclei. The pion-nucleon sigma-term also features in the leading density-dependence of the scalar quark condensate and in CP-violating \(\pi N\) couplings that contribute to electric dipole moments of the nucleon and light nuclei.

The \(\pi N\) sigma-term can most precisely be determined from a Roy-Steiner (RS) analysis of pion-nucleon scattering, using the precision pionic atom data from PSI that allow for an accurate extraction of the \(\pi N\) S-wave scattering lengths [12]. The RS analysis is in fact the first ever dispersive analysis of \(\pi N\) scattering with error bars. It leads to a high-precision determination of \(\sigma_{\pi N} = 59.1(3.5)\) MeV [13], which is quite an achievement in hadron physics. The strangeness sigma-term is less well determined; combining lattice QCD and chiral perturbation theory results leads to \(\sigma_s = 30(30)\) MeV. Consequently, only about 100 MeV of the nucleon mass are due to the Higgs. Stated differently, in a world with massless quarks, the proton would still weigh in with about 840 MeV, quite different from the pion, which would be massless in such a world due to its Goldstone boson nature. This is a central result of QCD! It should be noted, however, that present lattice QCD determinations of the pion–nucleon sigma-term are inconsistent with our knowledge of the S-wave pion-nucleon scattering lengths (see Ref. [14]). This is definitely a challenge to the lattice QCD community.

**Precision Shapiro Delay Physics**

In his seminal paper in 1915, Einstein proposed three tests of GR, namely the perihelion motion of Mercury, the bending of light by massive bodies, and gravitational waves. While the first was already observed earlier, light bending was seen by Eddington in 1919 and gravitational waves as predicted by GR were detected in 2015. In 1964, Shapiro had proposed a fourth test of GR, namely the time delay in a signal due to the reduction of the speed of light in curved space–time [15]. More precisely, light moves on geodesics and these are modified in curved space–time, leading to a delay in the arrival time of a signal. In the standard approximation for a binary system, where the signal is sent from the body A, the Shapiro delay is given in terms of two parameters (first post-Newtonian approximation), namely the Shapiro range, \(r_{sh} = Gm_B/c^2\), with G Newton’s constant, \(m_B\) the mass of the companion, and \(c\) the speed of light, and the so-called Shapiro shape, \(s_{sh} = \sin i\), with \(i\)
the inclination of the orbit. To this order in the expansion of \((v/c)^2\), with \(v\) the velocity of the companion, the predictions of GR agree very well with the data from the double pulsar PSR J0737-3039A and B [16]. An update of this work is depicted in Figure 2, where new measurements of the Shapiro delay in this system are shown. The delay is largest at superior conjunction (orbital phase of 90 degrees), when the emitting pulsar is located behind its companion as seen from Earth. The solid curve shows the expectation from GR. The remaining small deviations resulting from higher-order effects have been detected and will be discussed by an upcoming work in Ref. [17]. Higher-order propagation delays in the \((v/c)^2\) expansion for a binary system are: (1) retardation [18], (2) light bending [19], and (3) the pulsar rotation [20]. This fine prediction of GR is in remarkable agreement with the most recent data [17]. In fact, the theoretical uncertainty in the prediction of the Shapiro delay is about 0.02%, which is quite amazing.

Precision Meets Anthropic

Nuclear lattice effective field theory is a relatively new tool to perform \textit{ab initio} nuclear structure and reaction calculations at the subpercent level (see, e.g., a recent monograph [21]). In an earlier article in this journal [22], I had already discussed how this framework can be used to investigate the closeness of the so-called Hoyle state in \(^{12}\text{C}\) to the triple-alpha threshold as a function of the fundamental parameters of the SM. This energy difference plays an eminent role in the discussion of the so-called anthropic principle. I would like to mention that there has been a recent update on the calculation of the parameter-dependence of this quantity, partly triggered by new stellar simulations investigating the dependence of carbon and oxygen production in stars on the aforementioned energy difference, as well as on the star’s metallicity [23]. Also, the description of the quark mass dependence of the NN S-wave scattering lengths, that feature prominently in this calculation, has been improved, but still lattice QCD simulations closer to the physical point are needed to reduce the ensuing uncertainties (even worse, there is some sizeable tension between the existing lattice QCD determinations of the NN S-wave scattering lengths). The most interesting finding of this new work is that the scenario of no fine-tuning in the light quark masses can now be excluded. The interested reader is referred to Ref. [24] for a more detailed discussion and further references.

Summary and Conclusions

Let me briefly summarize the main lessons learned here:

1. Precision predictions rest on scale separations, therefore effective field theories are the best tool to make precision predictions (or other methods that can either deal with perturbative or nonperturbative physics in a systematic way).

2. Precision predictions, or, more generally, precision physics, are (is) of ever growing importance.

3. Precision physics is arguably our best take on discovering physics beyond the SM.

4. Consequently, we need to sharpen the predictions where the SM gives only a tiny contribution, such as the electric dipole moments of nucleons and light nuclei.

I hope that with this short article I conveyed the fascination related to precision physics. It sometimes might take a long time for such a prediction to be confronted with an equally precise experiment, but this should not stop us from investing more time and effort into this rewarding field, independent of the area of research one is working in.

Acknowledgments

I thank all my collaborators for sharing their insight into the topics discussed here. I am very grateful to Michael Kramer and Norbert Wex for teaching me the beautiful physics related to the Shapiro delay and double pulsar systems. Computational resources were provided by the Jülich Supercomputer Centre and the RWTH Aachen. The work was supported in part by the DFG, the Chinese Academy of Sciences, and the VolkswagenStiftung.
feature article

This article grew out of a talk at the first Joint ECFA-NuPECC-ApPEC Seminar at Paris in October 2019 (JE-NAS-2019) that brought together physicists from particle, hadronic and nuclear physics as well as from astrophysics and cosmology. I was asked to summarize the role of “precision predictions” at this meeting. Clearly, given the time constraints, this could only cover a very small fraction of all the intriguing results in the different fields and the choice of topics therefore had to be entirely subjective.

ORCID
Ulf-G. Meißner
http://orcid.org/0000-0003-1254-442X

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CRIB: The Low Energy In-Flight RI Beam Separator

Introduction

The Center for Nuclear Study (CNS) low-energy radioactive ion beam separator (CRIB) is owned and operated by the University of Tokyo and located at the RIKEN Nishina Center Radioactive-Isotope Beam Factory (RIBF) [1, 2]. In this article, we introduce this class of separator, provide an overview of CRIB’s history, describe the facility’s design, give an outline of recent results, and conclude with details on our philosophy and how to join the CRIB collaboration.

Because it produces low-energy, in-flight, radioactive beams, CRIB is sometimes misclassified with either much higher energy in-flight facilities that use fragmentation/fission or alternatively with low-energy facilities using the isotope separator on-line (ISOL) method. Low-energy, in-flight separators are a distinct class of radioactive beam facilities, which besides CRIB include those installed at Argonne National Laboratory (RAISOR), Florida State University (RESOLUT), Laboratori Nazionali di Legnaro (EXOTIC), Texas A&M University (MARS), and the University of Notre Dame (TWIN-SOL), to name several examples. This category of radioactive beam facility is distinct by impinging beams of heavy ions on lighter targets at low energy (typically <10 MeV/u, with some exceptions) in order to produce radioactive beams near the valley of nuclear stability using two-body reactions. Compared to either fragmentation or ISOL facilities, the infrastructure required to realize such low-energy, in-flight separators is relatively reduced.

Historical Context

CRIB has been in operation since 2001. The facility was envisioned some time after a redistribution of the former Institute for Nuclear Study (INS), the University of Tokyo, in the 1990s, which included the creation of a new High Energy Accelerator Research Organization (KEK) among other noteworthy institutions. At the time of the dissolution and redistribution of nuclear physics efforts of the University of Tokyo, several professors from INS with interests in low- and medium-energy nuclear physics remained unplaced, and thus CNS was created in 1997 and continued operation of the SF cyclotron at the former INS campus in Tanashi, Tokyo. However, the university later decided to close down the Tanashi campus. At that time, two future plans were proposed for CNS: to build a medium-sized cyclotron facility in Kashiwa, Chiba, or to make a joint collaboration with the Institute for Physical and Chemical Research (RIKEN) in Wako, Saitama. Around 1999, the latter plan was finally adopted and CNS moved to the RIKEN campus, where it has remained ever since. The success of the joint venture of CNS interfacing between the University of Tokyo and RIKEN has been evidenced from the ion source team through to endline apparatuses including not only CRIB, but also, for example, the more recent SHARAQ and OEDO systems. By now, CNS—and more recently the Wako Nuclear Science Center, KEK—are officially recognized as co-operators of the world-famous RIBF facility, demonstrating the success of the University of Tokyo’s reorganization venture.

Although an initiative was underway at INS in the mid-1990s to install an ISOL facility for low-energy radioactive beam studies, the university’s realignment plan meant a new vision was required if one wanted a low-energy radioactive beam. At the main RIKEN campus in Wako (only ~10 km north of the old INS site in Tanashi), a modest experimental hall at the RIKEN Accelerator Research Facility enumerated E7 contained equipment no longer in use. When approached with the idea for a low-energy, in-flight, radioactive beam separator to be installed in this hall by a new collaboration, the director at the time quickly agreed. Concurrently, a decommissioned spin spectrometer of Osaka University, known as DUMAS, had been activated by its use, and was likewise sitting unused in the western region of Japan. All parties finding the situation agreeable, CNS led the effort to relocate DUMAS to the main RIKEN campus to be repurposed as part of the in-flight separator CRIB, shown in its present form in Figure 1. A number of refurbishments were needed, including repolishing of all vacuum parts and the installation of a beam stop inside the first magnetic dipole D1, as well as careful installation and alignment, which were accomplished with assistance from Sumitomo Heavy Industries, Ltd. A windowless gas production target was made (superseded, see below), and a newly designed Wien filter (described below) was added to the end of the beam-line.

Despite an experimental hall directly under a modest K~70 AVF cyclotron being clear of space for several sophisticated magnets and vacuum systems, a number of developments were still required to realize the vision of CRIB. The ion-beam optics of the vertical plane for CRIB...
is twisted by about 15 degrees at the vertical transport part, which is precisely corrected by installing a pair of rotatable quadrupole doublet magnets. Considering the AVF cyclotron's capabilities and the relatively significant energy loss experienced by low-energy, heavy ions traversing matter, high charge-state beams are desirable, as the beam energy $E$ from a cyclotron is proportional to the square of the ion charge $q$ ($E \propto q^2$). Such points had not been a major priority before CRIB, when the AVF was just an injector to the RIKEN Ring Cyclotron. Thus, the ECR ion source technologies pioneered at INS were needed, and CNS installed (and continue to develop) two such ion sources at RIKEN. Particularly for low-energy, in-flight RIB facilities, a variety of primary beam species are needed to produce a diverse range of radioactive beams. Thus, continued developments by the ion source group for the AVF cyclotron have been and continue to be extremely critical for the success of CRIB. These ion source techniques continue to provide high-quality, intense beams to many portions of RIBF, such as BigRIPS up to the present. Improvements in the beam intensity and emittance from the AVF cyclotron have improved year by year with upgrades including the installation of the flat-top mode operation and the K-number increase of the cyclotron by 10%. As cyclotrons use radio frequency (RF) oscillating electric fields to accelerate charged particles, the beam must also be bunched prior to injection to the cyclotron and extracted efficiently. The largest transmission loss from the ion source to the experimental focal planes of CRIB occurs just before and after the cyclotron acceleration; as the present efficiency between the Hyper ECR ion source and CRIB is 10–20%, it is clear that these technical developments and upgrades have been crucial for the production of intense radioactive beams. The phase-space qualities, such as spot size and divergence of the beam ions, must also be excellent to achieve efficient radioactive beam collection at low energy, and thus the entire beam-line system from beginning to end needs to be evaluated and controlled carefully in low-energy, in-flight separators.

**Design Concept**

The Jacobian transform that quantifies the details of momentum conservation serves as one of the foundations for radioactive beam production at CRIB and other in-flight facilities at all energies. The history of ion beams has led momentum conservation to be categorized into two basic groups of kinematics, called normal kinematics and inverse kinematics, tending to describe the case where the beam is lighter or heavier than the target, respectively. As an aside—nuclear physics and astronomy coincidentally share a similarity in historical nomenclature. In astronomy, everything heavier than hydrogen and helium is usually called metals whereas in nuclear physics beams of hydrogen and helium are distinguished as light ions from everything else, which are usually considered as heavy ions.

A key feature of impinging a primary beam of heavy ions on a light target material is that the heavy recoils (the secondary radioactive beam ions of interest) are focused into a cone with a small angular dispersion in the laboratory, facilitating the efficient collection and purification of the secondary ions. These secondary beam ions have a similar (but slightly lower) energy than the primary beam, so that re-acceleration is not necessary, and the initial secondary beam energy is instead tuned by selection of the pri-
ary beam energy and the production target thickness.

Considering that energy loss goes more than a power of the nuclear charge, $Z$, light target materials such as hydrogen and helium not only allow one to exploit the above inverse kinematics but also to minimize the energy loss and straggling of the beam in the target material. The typically preferred radioactive beam production reactions are thus, for example, $(d,n)$, $(d,p)$, $(p,d)$, $(p,n)$, $(^3\text{He},n)$, and so on. These reactions typically have large, favorable differential cross-sections of several to hundreds of millibarns per steradian.

Both challenges and advantages are encountered by the fact that hydrogen and helium tend to be naturally found in a gaseous state. The presently available beams (and their parameters) are available on the CRIB website\(^2\) and are also shown in Figure 2.

As mentioned above, species of hydrogen and helium are well suited as production targets and being naturally gaseous the production target thickness can be precisely optimized by controlling the gas pressure. At CRIB, up to 1 atm of target gas is confined in an 8-cm-long, windows gas cell.\(^3\) A cryogenic target system, in which the target gas can be cooled down to about 90 K with liquid nitrogen, has been in operation since 2006. The cryogenic temperature makes the target gas three to four times thicker and provides a better cooling efficiency considering the heat deposited by the beam. One main feature of the CRIB cryogenic target system is forced circulation flow of the target gas. We have found that the circulation of the target gas at a rate of 55 standard liters per minute was effective in eliminating density reduction caused by heat deposition of the beam [4], where we succeeded in producing an intense $^7\text{Be}$ beam of $2 \times 10^8$ pps using this system (about a factor 10 higher than without gas circulation).

The secondary beam is first momentum selected with a magnetic analysis using two mirror-image dipole magnets (D1 and D2, as shown in Figure 1). The cocktail beam is subsequently purified with a Wien filter (installed in 2003), which separates the beam ions according to their velocities. The Wien filter is operated with high voltages of $\pm 50–100$ kV, supplied for a pair of 1.5-m-long electrodes with a gap of 8 cm. The increase of beam purity after the Wien filter is dramatic, and many successful CRIB experiments would be otherwise impossible without it.

For relatively light radioactive isotope (RI) beams such as $^7\text{Be}$, we can obtain an excellent purity of $>99\%$ after the Wien filter. In the case of medium-mass RI beams, Figure 3 shows the particle identification for $^{30}\text{S}$ before the Wien filter, where the purity is subsequently increased by approximately three orders of magnitude [5]. The particle identification plots show an advantage of using bunched beams in the driving accelerator: the cyclotron’s RF signal can be coupled with a beam-line monitor to make time-of-flight measurements to assist with identifying the species of radioactive beam ions event by event.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{CRIBなんか.png}
\caption{Chart of radioactive beams previously produced at CRIB. Species are plotted in the customary manner: the horizontal axis is neutron number; the vertical axis is proton number.}
\end{figure}
facilities and methods

Experimental Results

Using these beams, a number of diverse experiments and applications are possible at CRIB. Many in-house detector systems are available to collaborators, as well as a large scattering chamber (roughly one cubic meter) with many flanges and feedthroughs to accommodate dedicated systems provided by collaborators. Below we outline some of the main accomplishments at CRIB within the last several years.

Proton Resonant Scattering and \((p,\gamma)\) Reaction

Hydrogen burning is a fundamentally important and basic process within nucleosynthesis, considering that hydrogen is the most abundant element in the universe. In high-temperature hydrogen burning, numerous \((p,\gamma)\) reactions on proton-rich nuclei become particularly relevant; these sites include first-generation stars, X-ray bursters, novae, supernovae (\(vp\)-process and \(vp\)-process), and so on. Unfortunately, rather limited information is available for astrophysical reactions with unstable nuclei. Our knowledge is fundamentally limited owing to the experimental challenges and difficulties involved in working with radioactive nuclides.

One method to study resonances in the compound nuclei contributing to \((p,\gamma)\) reactions is proton resonant scattering with the thick-target in inverse kinematics method. Many measurements of proton resonant scattering have been performed successfully since CRIB started its operation, and we highlight only some more recent works:

- \(^{22}\text{Na} + p\) for destruction of the \(\gamma\)-ray emitter \(^{22}\text{Na}\) \[6\];
- \(^{21}\text{Na} + p\) for the \(^{25}\text{Al}(p,\gamma)\) reaction \[7\];
- \(^{26}\text{Si} + p\) for the \(^{26}\text{Si}(p,\gamma)\) reaction \[8\]; and
- \(^{26m}\text{Al} + p\) for the \(^{26m}\text{Al}(p,\gamma)\) reaction using a novel isomeric cocktail beam \[9\].

Direct and Indirect Study of \((a,p)\) Reactions

In hot hydrogen burning processes, \((a,p)\) reactions with unstable nuclei also play important roles. The \(^{14}\text{O}(a,p)\) reaction is considered as a critical breakout route from the hot-carbon-nitrogen-oxygen (CNO) cycle region to higher mass regions, which is followed by the \(rp\)-process. In the intervening \(ap\)-process, a sequential chain of \((a,p)\) and \((p,\gamma)\) reactions accelerates nucleosynthesis of proton-rich nuclei, much faster than the normal \(rp\)-process as beta-decays are not necessary in the trajectory to higher mass. The rates of these \((a,p)\) reactions are considered to be crucial to our understanding of explosive astrophysical phenomena, particularly X-ray bursts and core-collapse supernovae. CRIB is a particularly suited facility to investigate these \((a,p)\) reactions, considering the experimental and astrophysical matching between the relevant energies and the radioactive species involved. Experimental data for these reactions are relatively sparse, and we have already obtained valuable information to determine many such reaction rates more precisely. Recent works include:

- \(^{17}\text{F} + p\) for the \(^{14}\text{O}(a,p)\) reaction \[10\];
- \(^{21}\text{Na} + p\) for the \(^{18}\text{Ne}(a,p)\) reaction \[11, 12\]; and, most recently, in 2019, \(^{25}\text{Al} + p\) scattering in order to evaluate the reaction rate of \(^{22}\text{Mg}(a,p)\).

We have performed a series of direct studies on astrophysical \((a,p)\) reactions for \(^{11}\text{C}(a,p)\), \(^{14}\text{O}(a,p)\), and \(^{21}\text{Na}(a,p)\) with a standard helium gas target and for \(^{18}\text{Ne}(a,p)\), \(^{22}\text{Mg}(a,p)\), and \(^{30}\text{Si}(a,p)\) with an active target, the in-house GEM-MSTPC. We determined the reaction rate of \(^{14}\text{O}(a,p)\) down to the center-of-mass-energy of 2.2 MeV, partially resolving previous discrepancies in the magnitude of the cross-section and the probability of 2-proton decays \[13\]. We carried out a direct measurement of \(^{11}\text{C}(a,p)\), and an intricate time-of-flight separation was used to identify the excitation exit-channel nucleus successfully in one of the most thorough measurements of its type \[14\]. We also conducted a number of measurements with a new active target system, where
the first science results were published for $^{30}\text{S} + \alpha$ for X-ray bursts [5].

Studies on $(\alpha,\gamma)$ Reaction and $\alpha$-Cluster Structure Via $\alpha$ Resonant Scattering

Proton resonant scattering is a fundamental and well-established method used at CRIB. By replacing the hydrogen target with a helium gas target, $\alpha$ resonant scattering can be measured with the same method, enabling us to study $\alpha$-induced astrophysical reactions or $\alpha$-clustering phenomena. Figure 4 shows two experimental set-ups with $^7\text{Be}$ and $^{10}\text{Be}$ impinging on helium gas targets. Although we often use solid CH$_2$ targets for proton-scattering measurements, we have also used hydrogen gas targets [6–8] to reduce possible contributions from carbon nuclei. First, we used a stable beam to investigate $^7\text{Li} + \alpha$ resonant scattering [15]. As a follow-up, we performed a similar experiment for the $^7\text{Be} + \alpha$ system [16]. These $(\alpha,\gamma)$ reactions play a role in astrophysical scenarios at high temperature. From the perspective of nuclear structure, antisymmetrized molecular dynamics (AMD) reproduced the experimental moment of inertia and bent structure interpretation. We also performed a study on the $^{10}\text{Be} + \alpha$ system, where exotic $\alpha$-cluster structures are predicted. A new theoretical prediction of a linear-chain state in $^{14}\text{C}$ was made by Suhara and Kanada-En’yo with an AMD calculation in 2010 [17]. We obtained an excitation function (Figure 5) where we identified three resonances with unprecedented correspondence to the theoretically predicted bands [18]. Despite the agreement between the theoretical and experimental energy levels in $^{14}\text{C}$, the existence of this linear-chain state still cannot be regarded as unambiguous because of possibly unresolved resonances and possible background arising from secondary beam contamination and/or inelastic scattering. In order to resolve this issue, we initiated another experiment (CHAIN) at the INFN-LNS tandem. The experiment was carried out successfully in 2018, and the analysis is underway.

Indirect Methods

Considering the difficulties to measure astrophysical reaction cross-sections directly at the relevant energies, a number of indirect techniques are used. One such method is to use a grazing reaction to measure the asymptotic normalization coefficient of a reaction. At CRIB we used a radioactive beam to investigate the $^{12}\text{N}(p,\gamma)$ reaction with this method [19]. Further difficulties arise when many components could contribute to the low-energy cross-sections. The Trojan Horse Method (THM) treats a special region of kinematics within a transfer reaction and multi-ejectile measurement to extract these cross-sections. At CRIB, we pioneered usage of radioactive beam studies via the THM for the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction [20]. In 2015, we made a new, higher-statistics measurement, and the analysis is in progress. We also extended on previous works for the $^7\text{Be} + n$ for the cosmological lithium problem. We focused on precision measurements for the outgoing channels via the THM [21]. Here we emphasize that the CRIB collaboration is open to all experimental techniques, provided there is a compelling experiment design, proposal, and team. Complementary measurements and supporting all methodologies are at the heart of our collaborative philosophy.

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facilities and methods

Application of $^7$Be

The intense RI beams we developed at CRIB are useful not only for nuclear physics measurements but also for other applications. $^7$Be is a relatively long-lived RI (half-life 53 days) and was coupled uniquely with another beam of $^{22}$Na (half-life 2.6 years). The idea was to implant different isotopes in materials to diagnose wear of machine parts externally, one isotope for each of two sides. We performed an irradiation test at CRIB in close collaboration with the Industrial Cooperation Team at RIKEN (A. Yoshida et al.), and we were granted a patent for this new method in machine part analysis as a proof of principle (Japanese Pat. No. 6508650).

Implantation techniques are useful for fundamental nuclear physics studies. We collaborated with RCNP, Osaka University (A. Tamii et al.), to produce a $^7$Be-implanted gold target. The target production was motivated by a direct measurement of the $^7$Be(d,p) reaction, which is also a possible destruction reaction of $^7$Be in the Big-Bang nucleosynthesis. The implanted target was transferred to JAEA, where a measurement of the $^7$Be(d,p) reaction was made.

Reaction Mechanism

The RI beams available at CRIB often have energies on the same order of the Coulomb barrier height with heavier nuclei. Recently, we measured the systems of $^8$B+Pb and $^{17}$F+Ni.

For the former experiment, a $^8$B beam was produced at 7 MeV/u and $1-2 \times 10^8$ pps and irradiated at a lead target of 2.2 mg/cm$^2$. The energy of this $^8$B beam is unique to CRIB. Elastic scattering events were detected with the EXPADES detector array (from INFN-LNL, Italy) [22]. The latter $^{17}$F+Ni experiment was performed under collaboration with CIAE, Beihang University, and IMP-CAS (China). We measured elastic scattering of $^{17}$F+${}^{208}$Ni at several energies near the Coulomb barrier [23].

Most recently, the INSPIRATION project was initiated in 2019, where we measured scatterings and break-up reactions of the $^8$B+$^{120}$Sn system.

Collaboration

The CRIB group has an open-door policy: everyone is welcome to collaborate. As part of the RIKEN Nishina Center, scientific proposals for CRIB are reviewed in general by the RIBF Nuclear Physics Program Advisory Committee (NP-PAC) each year just like other devices. At present, the NP-PAC meets in December and a call for proposals is made in the late summer or early autumn each year. A major point to note is that the RIBF NP-PAC requires either the spokesperson or their designated representative (e.g., another colleague or a local CRIB member) to present the proposal in person as well as fielding questions from the PAC members before machine time can be approved. This can also be a good chance to visit the RIKEN campus, tour the facility, check the status of any necessary hardware, as well as to have fruitful discussions in person with the local members in a direct and casual manner.

While the scientific cases are reviewed with the same level of scrutiny as any other portion of the RIKEN Nishina Center, it should be noted that CRIB can in principle run in parallel to, for example, the SRC and BigRIPS beam-line. Thus, machine time scheduling for CRIB experiments can usually be allocated within a year of a proposal’s acceptance, and the spokesperson can often be granted a timeslot among their top choices at CRIB. We very strongly encourage all collaborators, especially new prospective users, to discuss their proposal with the CRIB team first. The main reason for such discussions prior to submission is so we can advise on the latest status of the facility or any recent technical developments; the spokesperson always has the final decision on whether to submit or not, so it is not a screening nor vetoing process. Unfortunately, not all experiments can be approved at the first proposal stage, but in general we found that, with few exceptions, most proposals are able finally to be granted machine time in modified form after several attempts.

Both the spokesperson and the local team are free to invite anyone to join a collaboration. We have found a number of advantages to such an open-door policy. Particularly in the case of a new collaboration, it goes without saying that both the spokesperson’s team (guests) and local team (hosts) may not be well acquainted, so it is unreasonable to delegate the task to a single individual or group. At the proposal stage, a successful future experiment needs to be evident in terms of the number of individuals as well as the collective expertise. While the typical turnaround time between an accepted proposal and a scheduled experiment at CRIB is usually short (as noted above), a number of the proposed collaborators finally encounter travel or scheduling problems. Thus, as scheduled machine time approaches, the CRIB group advertises upcoming experiments to its mailing list, not only to welcome past collaborators but to ensure enough shift members for a successful run.

CRIB places a strong emphasis on the education of the next generation of scientists, both through our open-door policy and the modest, self-contained nature of the laboratory. Visiting students are encouraged to shadow experts during experiment preparation, which includes vacuum systems, the radioactive beam production target, gas-filled detectors, solid-state detectors, the data acquisition system, specific details of the main experimental setup, and so on. Students that are sent to CRIB for the first time report a positive experience and most return to join subsequent experiments. For our col-
leagues taking long flights or from institutions with less funding, the CRIB group is often able to assist with finding means to reduce or offset costs.

We welcome you to CRIB!

Notes
1. Pronunciation: /siːɹɪb/ but never as /kɹɪb/, as in “see-rib” not a baby’s “crib.”
2. CRIB website available in Japanese and English language: https://www.cns.s.u-tokyo.ac.jp/crib/crib-new
3. As mentioned above, a windowless gas target was originally used, as described in Ref. [3], but is no longer in use.
4. E-mail: H. Yamaguchi, yamag@cns.s.u-tokyo.ac.jp, to join the mailing list.

References

Figure 5. Strong evidence for a linear-chain cluster state in $^{14}$C measured at CRIB [18].
Modern Alchemy to Fight Cancer

Introduction
According to the World Health Organization, cancer is the leading cause of death in many countries worldwide [1] and cancer incidences will continue to grow rapidly, with 18 million new cases and over 9 million deaths in 2018 [2].

In Canada, cancer is the number one cause of death, with half of all Canadians developing cancer over their lifetime and one quarter succumbing to cancer [3].

Because of these facts, the race is on for researchers and clinicians to find new and more efficient ways to diagnose and treat cancer. While surgery, chemotherapy, and external-beam radiotherapy are the main treatment options that are clinically applied, improvements in cancer diagnosis to detect many cancers in early stages make more selective and gentle treatment options possible.

The use of radionuclides for combined cancer diagnostics and treatment is finding increased application. Cancer diagnostics with radionuclides are either based on Single Photon Emission Computed Tomography or Positron Emission Tomography (SPECT). Both operate with ultralow concentrations of radiopharmaceuticals and are able to detect cancer with very high precision.

Targeted Radionuclide Therapy (TRT) is a promising treatment strategy. There are several emissions that can be used for TRT, including beta (β⁺) particles, α particles, and Auger electrons. These isotopes are attached to a similar or the same targeting molecule as for imaging, ensuring a targeted accumulation in the tumor. The subsequent emission can cause deadly damage to the cell by destroying crucial cell parts (e.g., DNA) [4]. Many of these isotopes can be produced via accelerators in an act of modern alchemy, transforming one element into another. TRIUMF—Canada’s particle accelerator center—has several unique proton accelerators to produce some of the most promising candidates for TRT. In this review, we discuss the principles of radionuclides and their necessary characteristics for TRT and the production routes that are available at TRIUMF.

Modern Alchemy (Radiochemistry) for Cancer Treatment
TRT is based on the delivery of therapeutic radionuclides to the tumor through delivery systems that have high selectivity to targeting cancer cells. Many of these delivery candidates (e.g., antibodies), are produced internally in the patient already to fight cancer and have an increased affinity to the cancer cells. Attaching radionuclides to these biomolecules causes irreparable damage to the cancer cells, while minimizing damage to surrounding healthy cells. Other targeting molecules (e.g., peptides or nanoparticles), can be applied for selective delivery to the tumor site as well through different affinity mechanisms.

The primary radiation emissions applied for TRT are β⁺ particles, α particles, and Auger electrons. The main difference between them is their difference in range and Linear Energy Transfer (LET), which can be simply explained as the density of ionization events along their track through matter, or in the case of cancer therapy, tissue [5]. Therefore, emissions with longer range are suitable for treatment of larger and solid cancer tumors, as particles release their energy over a relatively long distance (several millimeters) before they stop. In contrast, short-range emissions are more suitable to treat smaller tumors and metastases, for example at a distance of several cell diameters for typical α particles (Figure 1).

The application of β⁻ emitters for TRT is already well established in the clinic, with radionuclides such as 131I or 90Y to treat, for example, thyroid or kidney cancer. In these treatments, often no targeting molecule is needed, as the isotopes either naturally accumulate in the affected organ or can be inserted into micro-particles and then administered directly into the affected organ via blood veins. Recent successes with 177Lu make TRT a suitable treatment option for a larger range of cancer targets, in this case with specific targeting molecules, when other treatment options cannot be applied [6]. The larger range of β⁻ emitters enable them to penetrate millimeters in tissues before coming to a complete stop. Most of the suitable candidates for β⁻ therapy are neutron-rich isotopes and are typically produced via nuclear reactors.

Another potent emission for TRT are high LET α particles. These have recently shown very promising clinical results in the treatment of metastatic prostate cancer. This subgroup of TRT is called Targeted Alpha Therapy (TAT) [7]. However, there are two main limitations for TAT to become routine in clinical practice. First is the availability of α emitting radionuclides: Most candidates for TAT have high Z and are located relatively...
far from the line of stability. Often, radioactive targets and powerful reactors or proton accelerator facilities are necessary to produce clinically relevant quantities of α emitters. The second limitation is that most α emitters suitable for TAT have a decay chain with multiple radioactive daughters before reaching the stability line. This makes designing the delivery systems challenging, as the goal is to keep all radioactive daughters within the targeting cancer site. The localization of radioactive daughters increases the damage to the tumor and avoids unnecessary exposure of healthy tissue to the daughters, basically increasing the therapeutic outcome. Despite these challenges, initial clinical results show the extreme potency of TAT due to the combination of high LET and high energy (5–8 MeV), which make them extremely effective for small metastases: cancer that is typically very hard to treat. One of the most promising radionuclides for TAT is 225Ac (t₁/₂ 9.92 days), which can be delivered to the tumor attached to a selective delivery system. It is also promising as a parent isotope of 213Bi (t₁/₂ 45.6 minutes) and can be utilized as a generator source for this daughter, another potent TAT radionuclide [8]. At TRIUMF, we have established the production of 225Ac and synthesis of radiopharmaceuticals based on 225Ac [9] and are currently working on resolving the global supply issue by scaling the production with our 500 MeV cyclotron to clinical quantities.

Auger emitters also exhibit potential promise for TRT due to their high LET and very low energy (eV to keV range) compared with α and β emitters, which enable them to be very selective on the single cell level. In other words, Auger electrons will not penetrate more than one cell diameter and, if combined with an effective selective delivery, will damage only the targeting cell and none of the surrounding cells. The main question that scientists are currently working on is how close the Auger emitter has to be delivered to the cell DNA to cause sufficient toxicity for the effective TRT. At the moment, there are very few clinical trials ongoing with Auger emitters and most of the work is focusing on preclinical in-vitro and in-vivo work. Most of the existing work on Auger emitters is based on commercially available candidates (e.g., 111In), which are not necessarily the best choices for Auger therapy [10]. With TRIUMF’s unique production capabilities, the Life Sciences division is working to test and establish some of the promising candidates for Targeted Auger Therapy. There are several candidates that are currently being produced, including 197Hg and 119Sb.

TRIUMF’s “Hot Kitchen”

TRIUMF is Canada’s particles accelerator center, located in Vancouver, Canada. It has multiple unique capabilities for the production of well-established and rare medical radionuclides for imaging and therapy. Most radionuclides that TRIUMF is capable

![Figure 1. Difference in range and LET for TRT based on β⁻ (blue arrow), α (red arrow), and Auger (yellow arrow) emitting radionuclides.](image-url)
impact and applications

of producing are located on the neutron-deficient site from the stability line due to the availability of multiple proton irradiation facilities. However, access to the Isotope Separator and accelerator at TRIUMF (ISAC) and the capability of spallation reaction on the main cyclotron at beam-line 1A provide almost unlimited possibilities for the production of medical radionuclides [11]. Figure 2 provides an overview of radionuclides that are or can be produced at TRIUMF.

The following TRIUMF facilities are or will be used for medical radionuclides production (Figure 3).

The TRIUMF main cyclotron is one of the largest cyclotrons worldwide, with a proton energy of up to 520 MeV and currents up to 110 µA. The main cyclotron is TRIUMF’s core facility with four beam-lines to supply protons to various locations. One of the four beam-lines, 2C4, is utilized in the commercial production of 82Rb/82Sr generators for cardiac imaging. Another beam-line provides protons to the target stations at ISAC, which enable the production of radioactive beams of rare isotopes for many areas of research. The Life Sciences division is currently using the ISAC facility for the production of preclinical quantities of novel and exotic medical radionuclides. Over the past years, production, separation, and collection of 207/211At, 225Ac, 212Pb/212Bi, 165Er, and 155Tb were performed. The production with ISAC results in extremely high radio-nuclidic and radiochemical purity, which allows the use of these products as standard or references for production through other methods and gives the opportunity to explore the relative unknown chemistry of many of these isotopes.

Beam-line 1A is currently used for the production of clinical quantities of 225Ac via the spallation reaction on a thorium-232 target located at the Isotope Production Facility at the end of BL1A in front of the beam dump. This facility can irradiate targets completely symbiotically to the scientific beam delivery upstream and supplies much-needed quantities of 225Ac to enable many promising clinical trials that are currently restricted or on hold due to the limited quantities of actinium available. The main challenge in this production strategy is the co-production of hundreds of other fission products that require the development of robust and selective radiochemical separation to isolate 225Ac with sufficient radiochemical purity for further clinical application. In addition to isotopes of other elements, actinium isotopes are also co-produced and cannot be chemically separated. Of importance is the long-lived 227Ac (t½ 22.7 years), which may or may not significantly affect the patient dose, but can cause waste and storage issues, unless it can be separated by other means (e.g., via mass separation). Alternatively, to avoid the presence of radionuclidic...
Another beam line from the main cyclotron will deliver protons to the ARIEL facility, which is currently under construction and commissioning. The ARIEL facility will include a target station and beam dump, which can be used, similarly to BL1A, for the symbiotic production of $^{225}$Ac via the spallation reaction on thorium, or other medical isotopes of interest.

TRIUMF also has several low- to medium-energy cyclotrons for the production of medical radionuclides. Two 30 MeV TR30 cyclotrons are used for the production of some commercial medical radionuclides (e.g., $^{111}$In, $^{103}$Pd, and $^{123}$I). The TR13 cyclotron is the work horse of the Life Sciences Division and is mainly used for the production of positron emitters (e.g., $^{18}$F and $^{11}$C), for our clinical collaboration partners at the University of British Columbia for use in PET studies. It also produces radiometals for PET imaging (e.g., $^{68}$Ga, $^{44}$Sc, $^{45}$Ti, $^{90}$Nb, $^{89}$Zr), allowing our researchers and

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Figure 3. Schematic overview of the TRIUMF facility.
collaborators access to these more novel isotopes for medical imaging. The radiometals are varied by half-lives from one hour to several days, forming a “tool box” of radionuclides that can be combined and tested with various biomolecules to match their pharmacokinetics. In addition to imaging isotopes, the TR13 is also producing several therapeutic radionuclides for Auger therapy, including $^{197}$Hg, $^{119}$Sb, and $^{165}$Er.

The Institute for Advanced Medical Isotopes (IAMI) is one of the major infrastructure upgrades for TRIUMF and the flagship development of the Life Sciences Division. This facility will include a 24 MeV TR24 cyclotron, which will enable us to expand the variety and quantity of radioisotopes even further. IAMI will also have the required Good Manufacturing Practice environment necessary to translate novel radiopharmaceuticals into clinical application.

Conclusions

TRT is a very promising treatment strategy that enables the selective killing of cancer cells with minimal damage to surrounding healthy tissues. TRT is applied when other treatment options (e.g., surgery, chemotherapy, or external beam therapy) become inefficient or cause too much damage to the healthy bystander tissue and cause severe side-effects. TRIUMF is a world-leading hub for the production and application of many well-established radionuclides and novel and promising research candidates for targeted imaging and therapy.

References

1. https://www.who.int/news-room/fact-sheets/detail/cancer

Valery Radchenko
Life Sciences Division, TRIUMF, Chemistry Department, University of British Columbia, Vancouver, BC

Cornelia Hoehr
Life Sciences Division, TRIUMF, Physics Department, University of British Columbia, Kelowna, BC

Be sure to check the Calendar for upcoming events of interest to nuclear physicists.
PSI2019: The Physics of Fundamental Symmetries and Interactions Workshop Covered the Low-Energy, Precision, and Intensity Frontier

Peacefully grazing cattle on the green meadows of the Argovian landscape provide the distinct scenery outside the auditorium. Inside, the most precise present-day particle physics experiments are discussed and their results debated among 200 scientists from all around the world (Figure 1).

The workshop on the Physics of Fundamental Symmetries and Interactions (PSI2019) took place at the Paul Scherrer Institute, Switzerland, providing a second meaning for the acronym. It is already the fifth time that many of the world-leading efforts and collaborations met to discuss the progress and results in fundamental low-energy physics at the precision and intensity frontier. The program covered projects using muons, pions, antiprotons, and ultracold neutrons as probes, as well as atomic and molecular precision experiments and corresponding theory topics.

The workshop’s strategy and success were based on the selection of a distinct mix of 60 plenary talks reviewing subfields and presenting new results. No parallel sessions were held, but a highly esteemed poster session featuring 80 posters and a barbeque and drinks provided the ambience for engaged scientific discussions. In addition, all workshop attendees could elect with their votes three significant poster prizes (Figure 2) sponsored by NuPECC and handed over by NuPECC vice-chair Eberhard Widmann and workshop co-chair Klaus Kirch.

An important topic was charged lepton flavor violation, which was presented by an overview covering muon decay experiments at the main muon facilities worldwide. The anomalous magnetic moment of the muon ($g\text{-}2$) still provides a considerable headache for the Standard Model and was discussed in several also theoretical presentations, especially in light of the new experimental precision result on the fine structure constant and the appearance of a, still small, deviation also in the electron $g\text{-}2$ measurement when compared to the Standard Model.

The hot topic of the last years, the proton radius puzzle, was a central topic. The mystery appears to be closer to a solution, as new results from electron scattering as well as from several (but not all) new precision ordinary (electronic) hydrogen spectroscopy measurements appear to confirm the result obtained from muonic hydrogen spectroscopy.

New measurements using antiprotons and antihydrogen were presented from experiments at CERN’s antiproton facility, setting a new precision level on particle properties and CPT tests.

Electric dipole moments (EDM) were a prominent topic featuring two recent results from $^{129}\text{Xe}$ atoms. An overview of the worldwide activities on neutron EDMs was given with reports from selected experiments. Concerning
the electron EDM and future nuclear EDM measurements the perspectives of molecular techniques were highlighted.

Besides nEDM, various topics of fundamental neutron physics were covered, most prominently, new impressive results of neutron decay correlations and the recent worldwide discussion on discrepancies in measured values of the neutron lifetime. While the new high-precision measurements from Los Alamos and ILL using stored ultracold neutrons and measuring neutron disappearance confirm the lower value of the lifetime, the cold neutron beam experiment’s result from measuring the decay rate of neutrons to protons remains at a several standard deviations longer lifetime. Besides possible systematic effects of the experiments, other explanations involving nonstandard physics were discussed. Meanwhile, while most dark decay channels have been ruled out, a possibility involving neutron to mirror-neutron oscillations seems to not yet be completely off the table.

Searches for dark matter, axions, and Axion-like particles (ALPS) were covered from the theory and the experimental side, emphasizing searches with low-energy precision experiments.

Time measurements with a stunning 18-digit precision optical-lattice clock were presented, reaching sensitivities to test general relativity and searching for exotic physics in the lab.

Several efforts using exotic atoms for precision tests of QED, parity violation, and CPT completed the picture.

At the workshop dinner, with traditional Alphorn music and Swiss-style raclette, the participants were humorously reminded by the eminent neutron physicist Geoff Green why doing precision experiments all over again and again is justified and why measuring zero with always higher precision can be one of the most important things to do.

Besides the regular workshop program, participants made use of the possibility to visit PSI’s world-leading high-intensity muon and ultracold neutron facilities. In the end, there was the overall agreement that 2022 will see the next meeting in the PSIxxxx series with new and exciting results to be expected.


The 36th Mazurian Lakes Conference on Physics was organized by the University of Warsaw, the National Centre for Nuclear Research, and the Pro-Physica Foundation, and chaired by Wojciech Satuła (University of Warsaw) and Krzysztof Rykaczewski (vice-chair, ORNL Oak Ridge). It attracted 149 physicists from 25 countries and 66 institutions (Figure 1), among them a large number of young researchers who had the pos-
sibility to interact with more experienced scientists and present the results of their work. In total, 88 oral contributions and 68 posters were presented.

It is the tradition of the conference to begin with a general lecture, and this year it was on “Virtual unfolding of folded papyri” and was presented by Mahnke. On the first day, we benefited from lectures on the recent observations of gravitational wave signals to constrain the nuclear Equation-of-State (Bauswein), and on mass measurements helping to understand neutron star mergers (Aprahamian). Neutrino mass measurement within Project 8 was presented by Petitus, while Sakai reported on a search for the tri- and tetra-neutron. We continued with presentations on the physics of cold radioactive atoms (Sakemi), a nuclear clock based on ultra-low energy $^{229}$Th isomer (Thirolf), and two-proton radioactivity (Pfützner, Giovinazzo).

The science of super-heavy atoms was analyzed by Schwerdtfeger and Borschevsky, while Pachucki discussed nuclear charge radii derived from the isotope shift measurements in ordinary and muonic atoms. Nuclear structure calculations aided by quantum computers were presented by Morris, while Epelbaum, Magierski, Dobaczewski, Konieczka, and Hupin presented results on deuteron form-factors, exotic aspects of superfluid dynamics, density functionals, the $V_{ad}$ matrix element, and thermonuclear fusion reactions, respectively.

The nuclear astrophysics session covered the $i$-process (Wiescher), ($\alpha;\gamma$) reaction rates (Guttormsen), precise mass measurements (Kankainen), and the $d+^{7}$Be cross-sections for Big-Bang nucleosynthesis (Wiedenhöver). It was followed by a review of results from the RIKEN (Fukuda) and ISOLDE (Neyens), and progress achieved with radioactive-ion spin orientation technique (Ueno), Polarex (Thoër), nu-ball (Wilson), and precision beta-decay measurements (Kolos). This topic was continued with talks on ELI-NP (Ur) and Tb-IRMA-V (Cocolios). Schielzo summarized nuclear data needs for applications.

The super-heavy element session covered the status and perspectives of the SHE research at RIKEN, JAEA, and GSI (Haba, Nishio, Block) and theory predictions (Kowal, Skalski). Rasco and Grzywacz focused on fundamental aspects of beta-decay studies, while Płoszajczak discussed near-threshold effects.

The last session honored the recipients of the Szymański award (Menéndez), the Czosnyka prize (Wrzoszek-Lipska), and the best poster awards (Llewellyn, Bączyk, Lagaki, Saiz Lomas) sponsored by Nuclear Physics European Collaboration Committee (NuPECC). The conference was concluded by Lewitowicz presenting the NuPECC’s strategy for nuclear physics and Nazarewicz discussing the nuclear theory challenges.

A diverse social program, which included activities like sailing, with the one-race regatta won by a crew led by Thoër; a campfire with an international song contest; a classical music concert; and a crash course on the traditional polish dance “Polonez” at the conference dinner contributed to the unforgettable atmosphere of the conference. You are cordially invited to the 37th conference in the series, which will be held the first week of September 2021, again in the Mazurian Lakes district.

Chiara Mazzocchi and Wojciech Satuła
University of Warsaw

Krzysztof Rykaczewski
Oak Ridge National Laboratory

Magda Zielińska
CEA Saclay

African Nuclear Physics Conference 2019

Figure 1. Participants of the 2019 African Nuclear Physics Conference.
iThemba LABS, together with the local organizing committee with members from five South African universities and the international advisory committee, organized and hosted the first African Nuclear Physics Conference (ANPC 2019) series at the iconic Kruger National Park in South Africa from 1–5 July 2019. The goal of the ANPC is to establish an event that combines a topical nuclear physics conference with working group sessions aimed at focused discussions on select open questions in nuclear physics.

The topics of the ANPC 2019 were organized by conveners and focused on Nuclear Astrophysics, Nuclear Structure, Reactions and Dynamics, Fundamental Interactions, Neutron Physics, Heavy Ion Physics, Applied Nuclear Physics, and New Facilities and Instrumentation. The conference presentations were of very high quality and led to lively and extended discussions of the speakers with the audience.

During the three working group sessions the current theoretical and experimental status on low-lying dipole modes of excitation in nuclei were presented by top experts in the field. Each presentation was followed by in-depth discussions with the audience with a focus on specific key elements on how to solve some of the long-standing questions. Many colleagues continued the discussions well beyond the end of the sessions. On the final day, the delegates drew up an action summary on the way forward.

The ANPC 2019 was attended by 90 delegates from 22 countries (Figure 1), of whom 36 gave invited and 40 gave contributed presentations. South Africa had the most delegates with a total of 21 colleagues attending.

The evening prior to the commencement of the scientific program the delegates were treated to a traditional South African dance and braai under the star-lit sky. The scientific program made provisions for two half-day Safari excursions and a conference banquet with a late-night dance off. It is worthwhile to note that no delegates were lost to lions or harmed showing off their dancing skills.

Following the huge success of the first ANPC, we have already started with the preparations of the second installment of the ANPC. The event will once again feature the combination of a conference with a workshop dedicated to a specific “hot” topic in nuclear physics research.

Fañal Azaiez  
iThemba LABS

Mathis Wiedeking  
iThemba LABS and the University of the Witwatersrand
First Experiments at Extreme Light Infrastructure—Nuclear Physics

On 18 March 2020, the first experiments started at the international research center Extreme Light Infrastructure—Nuclear Physics (ELI–NP), for the study of the interaction of high-power laser pulses with matter.

The experiment aims to study the nonlinear optical effects in solid materials in order to shorten the duration of laser pulses. This will lead to a further increase of power and consequently of the irradiance in the focal spot for the experiments dedicated to nuclear research and applications.

This experiment is using the 100 TW output of the High-Power Laser System (HPLS). The beam parameters used were up to 2.25 J of compressed energy at 10 Hz at 800 nm central wavelength distributed on a \(\sim 1\text{ cm}^2\) spot on transparent target at 45° incident angle. The system is remotely operated from the laser control room, as illustrated in Figure 1.

This first experiment is the result of the planning and research carried out by the ELI–NP team in the last four years, together with the team of Professor Gerard Mourou, winner of the Nobel Prize for Physics in 2018, from Ecole Politechnique, IZEST, France.

Figure 1. The ELI-NP laser control room during the first experiment. The wall screen is showing the HPLS state machine, live diagnostics of the laser, vacuum control, environment monitoring, experimental area and target live view.

The ongoing experiment demonstrates the performance achieved by the operating team of ELI–NP and Thales, the supplier of the HPLS, to deliver laser pulses on demand for users of the research center (http://www.eli-np.ro/user_office.php).

The experiments to follow shortly are addressing electron acceleration and Betatron radiation with upscaling tests for the 1 PW and 10 PW outputs of the HPLS that were already commissioned and working in parameters since October 2019.

Ioan Dancus and Daniel Ursescu
“Horia Hulubei” National Institute for Physics and Nuclear Engineering (IFIN-HH)
In Memoriam: Leonard C. Maximon (1926–2020)

Leonard C. Maximon

It is with great sadness that we report the death of our special colleague, Leonard Charles Maximon. Max, as he was called by his friends and colleagues, passed away in his sleep on 4 January 2020, at the age of 94, in Phoenix, Arizona.

Leonard Charles Maximon was born in New York in 1926 on New Year’s Day. At the end of World War II he was learning to become a U.S. Navy pilot. He received his A.B. degree in Physics from Oberlin College in 1947. He was awarded a Ph.D. degree in Theoretical Physics from Cornell University in 1952 under the supervision of Hans Bethe. The significance of Max’s earlier work is captured succinctly by Freeman Dyson in the memorial issue of Physics Today in honor of Hans Bethe (2005).

Once, working on a problem in radiative corrections, he was able to solve a particularly troublesome mathematical expression, prompting the praise of a master such as Bethe who asked, “How did you do that?”

He was appointed as an assistant professor of applied mathematics at Brown University in 1951; a visiting professor at the Physics Institute of the Norwegian Technical University in Trondheim; a fellow at The University of Manchester, England; and then took a position on the staff of the Center for Radiation Research of the now National Institute of Standards and Technology (NIST), previously known as the National Bureau of standards (NBS). During that time, he was a visiting scientist and collaborator at the Center for Nuclear Studies in Saclay, France.

Max was a well-known expert in the applications and calculational aspects of quantum electrodynamics. He contributed extensively through his knowledge of radiative corrections to the work of nuclear experimentalists performing electron scattering experiments to extract information about nuclear structure.

While at NBS, he also collaborated with members of the Applied Math Division. His incredible ability to manipulate the special functions and their relationships led to his being consulted frequently. A few years ago, he served as an associate editor for Physics for the Digital Library of Mathematical Functions—a project emanating from the Mathematics Division of NIST. He authored or coauthored chapters on Bessel Functions and on the 3j, 6j, and 9j symbols used in quantum angular momentum coupling.

After a research career at NBS, leading to his recognition and election as a fellow of the American Physical Society, he began a second career with appointments at George Washington University (GW) and then, after a second “retirement,” at Arizona State University. At GW, he helped to revive research in astrophysics—where George Gamow and his students had once worked.

His many publications are known for their clarity and precision, including his recent Springer monograph entitled “Differential and Difference Equations—A Comparison of Methods of Solution.”

His humanity, humor, and caring nature will be missed deeply.

Ali Eskandarian, Donald R. Lehman, and William C. Parke
The George Washington University

Michael Crow
Arizona State University – Tempe, Arizona
In Memoriam: Emilio Chiavassa (1936–2020)

Emilio Chiavassa

Emilio Chiavassa, a scientist well known for his very high scientific standard and for his friendly and warm relations, passed away on 25 January 2020.

The life of Emilio had been exemplary both for his vast scientific and academic activity and for his strong commitment to the several institutional tasks vigorously undertaken by him for several years.

Born in 1936, he started his scientific career in the early sixties as an INFN researcher in Torino. His first activity concerned the construction of a neutron generator producing a 14 MeV beam, the related results representing an important reference for the nuclear physics community.

In the late 1960s, Emilio started to lead experimental activities with more international breadth. At CERN he was strongly involved in the study of pion–nucleon interaction and successively in pioneering experiments on hypernuclei. He also contributed to the construction of a large magnetic spectrometer devoted to a comprehensive experimental program on pion production in light nuclei collisions.

With the advent of the LEAR facility at CERN his interest moved to unique measurements of charge-exchange reaction induced by antiprotons.

At the beginning of the 1980s, Emilio’s career had an important leap when he was awarded with a professor chair in Nuclear Physics at the University of Torino.

A few years later, Emilio’s group moved to Saclay. There with the SATURNE facility equipped with the photon spectrometer PINOT built by his group, he did breakthrough work on meson production up to energies for eta-meson.

While in Saclay, Emilio, as in previous years, also put particular effort into identifying directions to stay always at the frontier and thus the idea of getting strongly involved in the search for quark deconfinement and Quark-Gluon Plasma (QGP) formation.

In 1990, with the Turin teams, he took on the new challenge of carrying out research with relativistic heavy ions at CERN, where an experiment to pinpoint one of the gold-plated signatures of QGP formation, namely the J/ψ suppression, was successfully conducted. A 2000 press release was titled, “A New State of Matter Created at CERN.”

With the advent of RHIC and LHC Emilio played a pivotal role in fostering an ample Italian participation in the ALICE experiment, and was chosen as the first Italian coordinator. For ALICE he was always a very important and inspiring leader, particularly for younger collaborators.

His legacy does not only concern research but also education and institutional work. One of us had the great privilege to be a member of the National Scientific Committee (Nuclear Physics) of INFN during his presidency and when she was appointed after him she realized that, without the training she had with him and his very precious advice, she could not have done the job. She is also aware, being a user of GSI (now FAIR), of how much he was appreciated as chair of the FAIR Scientific Committee (2004–2007).

Concerning education, he was inspired by his deep belief that research and teaching should be closely connected. He was also an innovator for topics and techniques, trained students and young researchers at all levels, and grew a group of successful colleagues. With Franco Bonaudi, he was the founding father of the school “Giornate di Studio sui Rivelatori,” which celebrates its 30th edition next year.

There is no doubt Emilio was gifted with uncommon human qualities and his informal, genuine, and convivial approach made him very popular among students and colleagues all over the globe.

The very touching condolence messages received from colleagues and many different institutions testify to the great and sincere appreciation for him and how much we will miss him for his outstanding scientific and human qualities.

We are two of these colleagues who are left with the solid belief of having been very privileged for having encountered him in our professional lives!

Ermanno Vercellin  
University of Turin

Angela Bracco  
University of Milano

Ermanno Vercellin

University of Turin

Angela Bracco  
University of Milano

Vol. 30, No. 2, 2020, Nuclear Physics News
The Finite Quantum Many-Body Problem: Selected Papers of Aage Bohr

This book contains 10 publications by Aage Bohr, covering the years 1951–1992, that have been selected by its editor, Ricardo Broglia. The papers are introduced by the director of the Niels Bohr Archive, Christian Joas, and by Broglia, who was himself a professor at the Niels Bohr Institute and a collaborator of Aage Bohr.

These papers concern two main scientific areas of the physics of atomic nuclei, and each of them is related to the spontaneous breaking of symmetries in nuclei—rotational symmetry and particle number symmetry. The former is due to the shell structure of independent particle motion in nuclei, and the latter is a consequence of the pairing interaction. Rotational symmetry is reflected in the formation of rotational bands, and particle number symmetry results in the formation of a super-fluid condensate or particle-vibrational states. When reading the papers, one is struck by the impressive breadth and depth of Aage Bohr’s perspective on physics and by the clarity of its presentation.

The interested reader can read the papers independently to get an impression, without the need to consult other texts. For researchers in nuclear physics, the papers provide a reminder of the skill with which Aage Bohr and Ben Mottelson, his close collaborator over the years, were able to develop their ideas using theoretical tools to gain far-reaching insight from the sparse experimental information available. For the many physicists who knew Aage Bohr and had the opportunity to talk with him, the reading awakens fond memories. Aage Bohr always approached physics problems with fresh eyes, and he and Ben Mottelson inspired the scientific work of two generations of nuclear physicists.

To appreciate the breadth and perspective of the topics covered by the book, it is useful to mention a few papers. The first paper, published in Physical Review in 1951, discusses the deformation of the nuclear shape at a time when there was little experimental information available. This work formed the first step toward a comprehensive understanding of nuclear deformation and rotational bands, for which Aage Bohr, Ben Mottelson, and James Rainwater were awarded the Nobel Prize in 1975. A later paper, entitled “Excitations in Nuclei,” presented at a symposium in Trieste, Italy in 1968, reviews the variety of excited states in nuclei as expected in general from quantum many-body physics. Surface vibrations result in coherent excitations of mean field states, and states generated by the transfer of a pair of nucleons in nuclear reactions lead to vibrations of the super-fluid condensate. The final contribution in the book is Aage Bohr’s speech in 1971 on the occasion of the 50-year anniversary of the institute founded by his father, Niels Bohr. Understandably, Aage Bohr here takes a look back at the foundation and early years of the Institute. He also looks forward, praising the new thinking regarding both research and teaching that springs continually from young colleagues and students.

Thomas Døssing
The Niels Bohr Institute,
University of Copenhagen, Denmark