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Cover Illustration: The Virgo gravitational wave detector is hosted at EGO near Pisa, Italy. Each interferometer arm is 3 km long. Picture credit: EGO/Virgo – see article on page 5.

APPEC, ECFA, and NuPECC Tighten Their Collaboration

The European Committee for Future Accelerators (ECFA), Nuclear Physics European Collaboration Committee (NuPECC), and AstroParticle Physics European Consortium (APPEC) are playing a major role in the development of particle, nuclear, and astroparticle physics at the European and international level. In particular, the 2020 Update of the Strategy for Particle Physics, together with 2017 NuPECC's Long Range Plan in Nuclear Physics and APPEC's 2017 Strategy for Astroparticle Physics, have defined a clear strategy for development of our disciplines in the coming years. These vision documents have also defined clearly a need for further close collaboration between our communities and between the three committees.

In order to tighten the links between the committees, in April 2018, NuPECC was invited as an observer to participate in the ECFA and Restricted ECFA (RECFA) meetings. NuPECC has returned the invitation to an observer from RECFA. Similar invitations were exchanged between ECFA and APPEC and APPEC and NuPECC, and today all three committees actively participate and report on their activities at their meetings.

One of the most important joint actions toward enhanced collaboration is the organization of the Joint ECFA–NuPECC–APPEC Seminars (JENAS). The first JENAS in 2019 in Orsay, France, attracted 230 participants and allowed astroparticle, nuclear, and particle physics researchers to present a broad panorama of their activities. The seminar has clearly shown that identified overlapping challenges can be transformed via joint programs into stronger opportunities to deepen our understanding of both the smallest and the largest structures in nature. To further explore topical synergies between the disciplines, a call has been issued for expressions-of-interest (EoI) for novel joint activities.

The success of the first JENAS encouraged our committees to organize the next seminar in Madrid, on 3–6 May 2022, hopefully as a face-to-face meeting.

The aforementioned call for JENAS EoI found an important echo in our communities. Five EoIs were submitted and endorsed by our committees (see http://nupecc.org/jenaa/?display=eois) :

- Dark Matter—Initiative for Dark Matter in Europe and beyond (iDMEu);
- Gravitational Waves for Fundamental Physics;
- Machine-Learning Optimized Design of Experiments (MODE);
- Nuclear Physics at the Large Hadron Collider; and
- Storage Rings for the Search of Charged-Particle Electric Dipole Moments (EDM).

The coordinators of the EoI, together with the representatives from our committees, have organized respective kick-off meetings and are in the process of defining their further activities.

Another important result of the joint efforts is the Diversity Charter (http://nupecc.org/jenaa/?display=diversity) prepared and endorsed by the three consortia. In the Diversity Charter, ECFA, NuPECC, and APPEC recognize the importance of diversity as a motor to boost productivity and innovation, fight prejudice and discrimination, and contribute to the improvement of social and economic standards.

The Diversity Charter is to be signed by research organizations, collaborations, and conference organizers in the fields of particle physics, nuclear physics, and astroparticle physics that value diversity and are committed to promoting equal opportunities at all levels.

After consultation with our communities, the Diversity Charter—and more precisely its part related to the monitoring of related data was revised and an improved version was released in May 2021 (see http://nupecc.org/jenaa/?display=diversity).

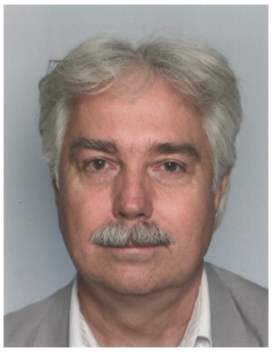
Important efforts of our committees are also focused on the recognition of individual achievements in large collaborations (http://nupecc.org/jenaa/?display=recognition). As a continuation of previous work by ECFA, which—among other activities—performed a community-wide survey in 2018, a dedicated joint working group was installed in July 2019 in Ghent. Key objectives of the initiative are: create awareness, initiate discussions inside collaborations, exchange and discuss best practices among all three communities, reflect on alternative or additional procedures, potentially perform a survey to monitor the progress on the topic, and report back to ECFA, NuPECC, and APPEC.

Recently, our committees got involved in the ECFA Detector R&D (research and development) Roadmap initiative (https://indico.cern.ch/event/957057/overview). The roadmap should identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics program in the near and long term, according to the priorities laid down in the Particle Physics Strategy. In order to identify synergies and opportunities with adjacent research fields, including astroparticle and nuclear physics, an advisory panel staffed with representatives of related research fields was established. The role of members of the advisory panel is to help establish communication between the conveners and experts in specialized task forces and the experts in their respective fields.

Opportunities for new joint activities are not limited to those mentioned above. The ongoing landscape analysis and evaluation process of new projects for the European Strategy Forum on Research Infrastructures roadmap, first calls for proposals of the European Union Horizon Europe framework program, collaboration between the theory centers the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (nuclear physics and related areas) in Trento and European Consortium for Astroparticle Theory (astroparticle physics) at the European Council for Nuclear Research and active participation in the European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures (ESCAPE) project, as well as a coherent outreach and training program are among the topics for which a joint approach of ECFA, NuPECC, and APPEC should be highly beneficial.

In the next few years, European particle, astroparticle, and nuclear physics will without doubt produce many exciting new results, facilitated by the new and upgraded frontline facilities progressively entering into operation. We believe that progress in science, and in our three disciplines in particular, will be driven by European and international cooperation. ECFA, NuPECC, and APPEC will concentrate their efforts to play a major and constructive role in this endeavor.

Karl Jakobs
Chair of ECFA



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Gravitational Waves as Probes for Nuclear Physics

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Gravitational-Wave Science

Gravitation is a main organizing principle in nature and determined the formation of large-scale structure in the early Universe. Some of the most important open problems in contemporary science are connected to gravitation, such as the origin of the acceleration of the Universe, commonly termed dark energy, and the existence of dark matter. While it is part of the Standard Model of Cosmology, and despite heroic efforts, so far dark matter has eluded direct detection. Alternatively, dark energy and dark matter may signal a breakdown of general relativity, our best theory of gravitation.

Gravitation is the least understood fundamental interaction and in an attempt to answer the many open questions, a large worldwide intellectual activity is ongoing, both on the theoretical front by studying the boundaries between general relativity, quantum field theory, and cosmology, and through experimental activities in astronomy (e.g., Planck, Euclid and the Vera C. Rubin Observatory), particle physics (e.g., the Large Hadron Collider at the European Council for Nuclear Research), and several dark matter searches (e.g., Xenon1T).

Gravitational waves are space-time curvature perturbations and constitute the dynamical part of gravitation. They travel at the speed of light and can be detected when they squeeze and stretch the space between the mirrors of an interferometer. Gravitational waves represent an ideal information carrier, suffering negligible scattering or attenuation between source and detector. The entire Universe has been transparent for gravitational waves, all the way back to the Big Bang, and they may constitute our only direct window onto the Universe to times as early as 10^{-34} s.

The first detection of gravitational waves happened on 14 September 2015, and the event was named GW150914 [1] (see Figure 1). Analyses revealed that it resulted from the merger of two black holes of 36 and 29 solar masses, respectively; within 0.2 seconds no less than 3 solar masses worth of energy was emitted in gravitational waves, making it then the most powerful astrophysical event ever observed.

GW150914 constitutes the first direct detection of gravitational waves, and it provided the first direct evidence of the existence of black holes. It revealed the merger of two black holes, and gave us access to the strong-field dynamics of pure space-time. The first observation run, so called O1, yielded two more detections: GW151012 and GW151226 [2]. All these observations were binary black hole (BBH) mergers and were reported by the LIGO Virgo Collaborations (LVC), but were made with the LIGO detectors only.

LIGO and Virgo as a Global Gravitational-Wave Observatory Network

The Virgo Collaboration currently consists of about 680 members from 124 institutes in 15 countries. Besides important data analysis work in the LVC, the Virgo Collaboration has realized Advanced Virgo, a 3-km arm-length power recycled Michelson interferometer with Fabry Perot cavities. Virgo is hosted at the European Gravitational Observatory (EGO) near Pisa, Italy (Figure 2).

After a 10-month commissioning break, the Virgo and LIGO Scientific Collaborations started the second Observing Run, "O2," on 30 November 2016, searching for gravitational-wave signals, initially with only the two LIGO detectors. GW170104 was the first event [3] in O2 in which a 50-solar-mass binary black hole coalescence was observed at redshift 0.2. On 8 June 2017, GW170608 was recorded [4]. This second O2 event originated from the merger of two 12 and 7 solar-mass black holes at redshift 0.07.

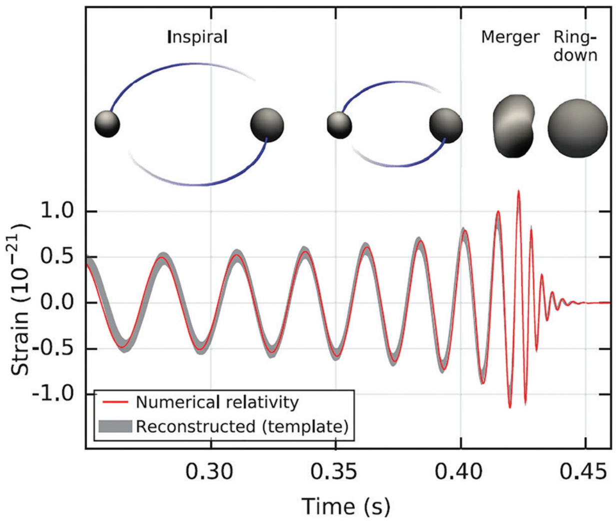

Figure 1. *Estimated gravitational-wave strain amplitude from GW150914. This shows the full bandwidth of the waveforms. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. The significance of the event was established to be >5.1σ. Picture credit: LIGO Scientific and Virgo Collaborations.*

Figure 2. *The Virgo gravitational-wave detector is hosted at EGO, near Pisa, Italy. Each interferometer arm is 3 km long. Picture credit: EGO/Virgo.*

The Advanced Virgo interferometer (Figure 2) joined LVC's observation effort toward the end of O2. The Advanced Virgo project realized an important increase of the sensitivity compared to the first incarnation of Virgo. For example, larger beams and heavier test masses (i.e., Virgo's core mirrors) were employed. The optical elements were of higher quality and featured improved lower loss coatings. The finesse of the main arm cavities was increased, which allowed to store up to 700 kW of laser power, leading to a reduction of shot noise and better sensitivity at high frequency.

Advanced Virgo was commissioned from May to July 2017 and on 1 August 2017, it joined the Advanced LIGO detectors. This 3.5-week joint LIGO–Virgo run was the first data-taking with three kilometer-scale interferometers. Virgo's performance was good, with the highest binary neutron star (BNS) range of 28.2 Mpc and longest stable lock stretch of 69 hours. Virgo's science duty cycle was about 85%. In this short period, Virgo contributed to the parameter estimation of no less than five gravitational-wave events [2], while 11 events were observed in O1 and O2 combined.

The addition of Virgo to the global network resulted in an increased data set because, besides the usual LIGO data, Virgo coincidence events with the LIGO–Louisiana and LIGO–Hanford detectors were also collected, while about 45% of the data were LIGO–Virgo triple coincidence events. Moreover, sky coverage (due to the complementary antenna patterns) and sky location of sources were improved. Determination of gravitational-wave polarization became possible, and the distance measurement was improved. Also, the threefold coincidence measurement resulted in increased robustness of gravitational-wave detection and provided an improvement in parameter estimation.

The first published three-detector observation [5] was made on 14 August 2017, at 10:30:43 UTC. The detected gravitational waves were emitted during the final moments of the merger of two black holes with masses about 31 and 26 times the mass of the Sun and located about 560 Mpc away. The newly produced spinning black hole has about 54 times the mass of our Sun. GW170814 was the first event that allowed the constraining of the polarization degrees of freedom of gravitational waves, giving strong support for tensor polarization.

Three days later, on 17 August 2017, at 12 : 41:04 UTC, LIGO and Virgo made their first observation of a BNS merger [6]. This BNS event, known as GW170817, produced a loud signal with a network signal-to-noise ratio of 32.4. The inferred median component masses with 90% credible intervals of the binary are 1.46 (+0.12, −0.10) and 1.27 (+0.09, −0.09) solar masses, with a conservative upper limit for the total mass of the system <2.8 solar mass (when restricting the prior to neutron star spins consistent with electromagnetic [EM] observations). With a 90% sky localization of 16 deg^2 and a luminosity distance of 40 (+7, −15) Mpc, this event constituted the closest and most precisely localized gravitational-wave signal yet. GW170817 was coincident within 1.7 s with gamma-ray burst GRB 170817A. At the same location and over a period of months, EM counterparts were seen spanning the entire EM spectrum from radio waves to X-rays [7].

BNS event GW170817 allowed a first determination of the Hubble constant where the distance was inferred from gravitational-wave information. Moreover, a nonzero tidal deformation could be extracted for various waveforms when assuming a low-spin prior. This allowed the first meaningful contributions of gravitational-wave science to both cosmology and nuclear physics. The significance of such results is expected to rapidly increase when the sensitivity of the detectors improve, especially at high frequency.

LIGO and Virgo started their third observation run, "O3," on 1 April 2019. In the first six months of O3, the so-called O3a run, a total of 26 candidate events were reported in near real-time through GCN Notices and Circulars. GWTC-2, the second gravitational wave transients catalog, was released on October 28, 2020 and reported on a total of 39 candidate gravitational wave events [15].

Among the 39 candidates, we find gravitational wave emission consistent with the coalescence of BBHs, BNSs, and neutron star-black hole binaries (NSBHs). The range of candidate event masses which are unambiguously identified as binary black holes (both objects with a mass in excess of 3 solar mass) is increased compared to GWTC-1, with total masses from about 14 solar mass for GW190924_021846 to about 150 solar mass for GW190521.

O3 science data taking was interrupted in October 2019 to allow for maintenance and commissioning of the detectors. Virgo's commissioning team successfully studied the noise sources limiting Virgo's sensitivity. Moreover, the injected laser power was increased from 18 to 26 W. These improvements resulted in Virgo's best sensitivity of 61 Mpc, a doubling compared to Virgo's sensitivity in "O2." Science data taking continued as O3b started on 1 November 2019. However, due to the COVID-19 pandemic, the run was suspended on 27 March 2020 to guarantee the safety of personnel at the observatories. The cumulative count of events and alerts is shown in Figure 3.

The most massive O3a BBH system is probably the one associated with GW190521 [16]. This system has a 98% probability of being the most massive, with a total mass of 163.9+39.2-23.5 solar mass and remnant mass of 156.3+36.8-22.4 solar mass. The least massive O3a system is associated with GW190425. This event is the second observation of a gravitational wave signal consistent with the merger of a BNS after GW170817 [8]. The estimated total mass is significantly higher than the masses observed by astronomers for such systems in our galaxy. GW190814's source [17] has a secondary with mass 2.59+0.08-0.09 solar mass, making its interpretation as a black hole or a neutron star unclear. GW190814 also has the most extreme mass ratio of all the candidate events, q = 0.112+0.008-0.009. GW190426_152155 is the candidate event with the highest false-alarm rate. Assuming it is a real signal of astrophysical origin, the inferred component masses raise the possibility that it could have originated from either a BBH or an NSBH source. The mass of the secondary component is consistent with masses of (previously) reported neutron stars.

The AdV+Project: Improving Virgo within the EGO-Site Boundaries

The Virgo collaboration will constantly improve the sensitivity of its instrument until it reaches the limits set by the EGO-site. The sensitivity of gravitational-wave detectors is determined by a number of fundamental noise sources, most importantly seismic and gravity gradient noise at low frequency, thermal and radiation pressure noise at mid frequencies, and shot noise at higher frequencies. Advanced Virgo is expected to reach a sensitivity betwen 90 and 120 Mpc in 2022, assuming that all technical noise sources will be understood and can be mitigated. AdV+is an upgrade project that improves on the sensitivity of Advanced Virgo by about a factor of two across a broad frequency range, with an expected completion of the project in 2025. In parallel, a similar upgrade project, A+, is being carried out by LIGO.

AdV+is carried out in a phased approach. In Phase 1 (2020–2022) the sensitivity is being improved by using frequency dependent squeezing and signal recycling. Signal recycling especially will improve the ability for source-localization, which is crucial for many of the scientific goals of gravitational-wave astronomy, such as EM follow-up, measuring the properties of compact binaries throughout cosmic history and cosmology. Frequency-dependent squeezing will reduce the fundamental quantum noise over the entire frequency range of the instrument. Note that squeezing was already successfully used by Virgo in O3 [9]. Sensitivity at low frequency will be improved through subtraction of gravity gradient noise. Phase 2 (2023–2025) will use larger beam sizes in combination with heavier mirrors and better coatings to overcome thermal noise. An increase of the beam power reduces shot noise, while an increase in the weight of the mirrors reduces the effects of radiation pressure. Virgo will improve its sensing and controls algorithms through machine and deep learning.

With the AdV+upgrade, Virgo will secure its scientific relevance in the global network of second-generation gravitational-wave detectors. This network possesses great potential in contributing to fundamental physics, astrophysics, astronomy, cosmology, and nuclear physics.

A Roadmap for Gravitational-Wave Science

The LIGO and Virgo global network has been expanded by the Kamioka Gravitational Wave Detector (KAGRA), an underground cryogenic interferometer with 3 km long arms, operated in Japan. KAGRA joined the global observatory network in 2020. Scientists from KAGRA [10] take

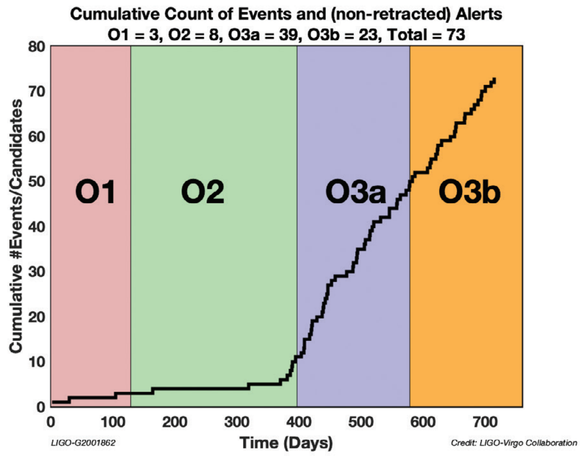

Figure 3. *Cumulative count of events and (non-retracted) alerts. Three events are observed in O1 and eight in O2. There are 39 events in O3a, the first six months of O3, and 23 non-retracted alerts have been issued in O3b. The rapid increase in event rate reflects the improvement in the sensitivity of the detectors. Picture credit: LIGO Virgo Collaborations.*

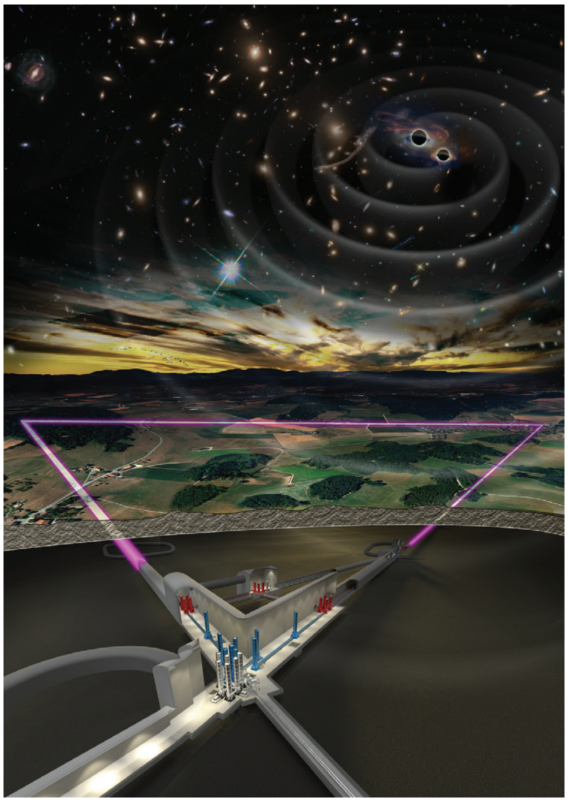

Figure 4. *Einstein Telescope is a third-generation gravitational-wave observatory that will be realized in Europe in the Belgium–Germany–Netherlands region or in Sardinia, Italy. Picture credit: Nikhef.*

a different approach by building their detector underground to suppress seismic and gravity gradient noise. In addition, KAGRA employs different mirror materials and coatings in combination with cryogenically cooling the mirrors to reduce their thermal noise. The design sensitivity for KAGRA is similar to that of LIGO and Virgo.

A+and AdV+are the upgrade projects recently started at LIGO and Virgo, respectively. The first phase of these projects is expected to be completed and commissioned in 2022, and will lead to an increase in the event rate by up to an order of magnitude. LIGO India (or Indigo) [11], a LIGO-like interferometer that is under construction in India, is expected to join the global network in 2025.

Figure 4 shows the third-generation observatory Einstein Telescope [12] that could be operational as early as 2035. A second 3G obervatory termed Cosmic Explorer [13] is under study in the United States. Finally, the Laser Interferometer Space Antenna (LISA) [14] is a space-based interferometer with a launch date in 2032 that may run in parallel with Einstein Telescope.

The third-generation detectors will scan the Universe for gravitational waves at redshifts as high as z = 100 to access the "dark ages," the era before the formation of the first stars. Each year they will detect up to a million gravitational wave events from binary sources distributed throughout the entire Universe. This will enable unprecedented cosmological observations (e.g., the study of the dark energy equation of state). Gravitational waves will be measured from the densest regions of matter, the earliest stages after the Big Bang, and the most extreme distortions of space-time near black holes, and this will lead to a better understanding of the origin and evolution of the Universe.

It is remarkable to envision that in a timespan of only two decades the detection of gravitational waves will go from discovery by the LVC in 2015 to the realization of Einstein Telescope, capable of detecting up to a million gravitational-wave events per year from sources distributed throughout the entire Universe.

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The Equation of State of Neutron Stars and the Role of Nuclear Experiments

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Introduction

Neutron stars (NSs) are unique laboratories to probe matter in extreme conditions not accessible in terrestrial laboratories. Indeed, with a mass of about 1 to 2 solar masses and a radius of about 10 km, NSs have densities spanning several orders of magnitude, exceeding in their core the density found inside atomic nuclei. While the properties of the outer layers consisting of a (solid) crust of nuclei embedded in an electron gas, together with a neutron gas in the denser region (possibly on top of a nuclear "pasta" mantle), and those of the outer core made of homogeneous asymmetric nuclear matter, can, to some extent, be constrained by nuclear physics experiments and theory, the nature of the NS inner core formed of strongly interacting matter at very high density still remains largely unknown [1].

The remarkable advances of multi-messenger astronomy on different dense-matter astrophysical sources has very recently led to the first quantitative measurements of various properties of NSs, such as the mass–radius relation [2–4] and the tidal polarizability [5].

These new observations, as well as the plethora of upcoming results from the LIGO/Virgo collaboration and those expected from the next generation of detectors, raise hopes in the near future to answer fundamental open questions such as the structure and degrees of freedom of baryonic matter in extreme density conditions, the occurrence of phase transitions, and the presence of deconfined matter in the core of NSs. In turn, these powerful new probes of ultra-dense matter have boosted the experimental and theoretical research on nuclear matter, and specifically the study of the nuclear-matter equation of state (EoS); that is, the functional relation $P(\rho_B)$ between pressure and mass-energy density of baryonic matter.

This direct connection between astrophysical measurements and the microphysics of dense matter is due to the fact that, under the unique hypothesis of validity of general relativity, there is a one-to-one correspondence between any static observable of mature and slowly rotating NSs and the underlying EoS. In particular, the Tolman–Oppenheimer–Volkoff equations of hydrostatic equilibrium allow associating the EoS to a unique relation between the mass M and the radius R of the NS [1]. This means that simultaneous measurements of mass and radius of different NSs would give a direct measure of the pressure of baryonic matter at given densities (more massive stars being associated with higher densities), thus a measurement of the EoS.

Unfortunately, the most precise measurements of NS masses concern binary systems, while radii have been recently inferred from the pulse profile modeling of X-ray data from (isolated) millisecond pulsars, making the observational mass–radius correlation relatively loose.

An especially interesting complementary observable is given by the tidal polarizability Λ, which measures the deformability of a compact object under the gravitational influence of a second body. The bijective correspondence between the EoS and the variation of the tidal polarizability with the star mass has been known since the 1960s, and a first measure of this parameter was provided by the LIGO/Virgo collaboration in the celebrated gravitational-wave event GW170817 [5].

Modeling the Neutron-Star EoS

The extraction of the dense-matter composition and degrees of freedom is complicated by the fact that there is no *ab-initio* calculation of dense matter in the nucleonic nor in the hadronic or partonic sectors, and effective models must be used instead (see Ref. [6] for a review). In order to extract the nuclear EoS from the gravitational waveforms, agnostic inference is therefore used, such as to explore all the possible shapes of the $P(\rho_B)$ functional [7]. The standard method consists in parametrizing the EoS with piecewise polytropes, subject to general physics constraints, such as causality, the respect of the unitary limit, and the asymptotic properties of lattice quantum chromodynamics. Many alternative, powerful techniques have also been proposed, such as spectral function expansions, parametrized sound speed models, as well as nonparametric inference based on Gaussian processes ([7] and references therein). The domain is evolving fast, and this collective effort is leading to a model-independent prediction of the different NS properties, based on constraints given by the various astrophysical observations.

However, this considerable progress is not sufficient to pin down the microscopic structure and properties of the ultra-dense baryonic matter composing the NS. Indeed, whereas a given macroscopic $M(R)$ or $\Lambda(M)$ curve is univocally associated with a microscopic $P(\rho_B)$ functional, identical EoSs can be obtained under different hypotheses on the underlying microphysics. Indeed, whatever the effective model employed, the energy density of baryonic matter depends on the different conserved charges of the strong interactions, namely the baryonic, charge, and strange numbers. On the other hand, the gravitational pressure only imposes the total energy density. The relative proportion of the different densities is determined by weak interactions, which are in equilibrium inside the NS, but the condition of chemical equilibrium explicitly depends on the (model-dependent) energy functional.

Therefore, a way to extract information on the structure and properties of dense matter is to use EoS parametrizations that cover the parameter space of effective nuclear models, under the different hypotheses on the effective degrees of freedom at high density. Presently, the tighter constraints are obtained in the case of purely nucleonic models, which are routinely optimized and calibrated over a plethora of experimental nuclear data.

Parametrizing the EoS with a functional that can explore the complete parameter space of nucleonic EoSs is known as nucleonic meta-modeling [8]. It consists of introducing a flexible energy functional able to reproduce existing effective nucleonic models, as well as interpolate between them. The parameter space being regulated by our present theoretical and experimental knowledge of nuclear physics, this technique allows to predict the astrophysical observables with controlled uncertainties. Moreover, it can be used as a null hypothesis to infer from the astrophysical data the presence of exotic non-nucleonic degrees of freedom. Nucleonic meta-modeling consists in a density or Fermi momentum expansion of the energy per particle of infinite nuclear matter composed of neutrons and protons with respective densities n_n and n_p.

In particular, a Taylor expansion around the saturation density n_0 allows the separation of the low-order derivatives, which are better determined by nuclear theory and experiments, from the high-order ones, which contain the highest uncertainties [9]. Schematically, we can write, at the order N:

$$e^N\left(n_n, n_p\right) = t^{FG} + \sum_{k=0}^{N} \frac{1}{k!}\left(v_k^{is} + v_k^{iv}\delta^2\right)\left(\frac{n-n_0}{3n_0}\right)^k \qquad (1)$$

where we have singled out the dominant degenerate Fermi gas contribution $t^{FG}\left(n_n, n_p\right)$, and defined the total baryonic density $n = n_n + n_p$ and the neutron–proton asymmetry $\delta = \frac{n_n - n_p}{n}$. The isoscalar (isovector) coefficients v_k^{is} (v_k^{iv}) can be one-to-one connected to the so-called empirical parameters [6, 9], given by the successive derivatives of the energy functional at saturation:

$$X_k^{is(iv)} = \left.\frac{\partial^k e^N_{0(sym)}}{\partial n^k}\right|_{n=n_0,\delta=0}, \qquad (2)$$

where e_0^N is the energy of symmetric $n_n = n_p$ matter, and the density-dependent symmetry energy is defined as $e^N_{sym} = \partial^2 e^N / \partial \delta^2 \,\big|_{\delta=0}$. For realistic applications, the expansion Eq. (1) is slightly complexified, introducing the extra density dependence induced by the effective mass, a low-density correction enforcing the zero-density limit [9], and a specific treatment of the NS crust [10]. This ensures a unified EoS treatment, meaning that the same nuclear model is applied in the different regions of the NS, which is crucial to avoid ad-hoc EoS matching that may introduce unphysical effects in the NS modeling [11].

The low-order empirical parameters (up to k=2) are relatively well constrained by *ab-initio* nuclear theory and low-energy nuclear experiments. On the theory side, an impressive progress has been made in the chiral perturbation theory of nuclear interactions, with a diagrammatic expansion that allows a reliable estimation of the uncertainties due to the missing terms [12].

On the experimental side, the low-order empirical parameters have been extracted by a systematic comparison of density functional approaches with a large set of high-precision nuclear observables, such as masses, skins, electric dipole polarizability, isobaric analog states systematics, flows in heavy-ion collisions, and collective modes (see Refs. [6, 9, 13] for a review, and references therein).

A (nonexhaustive) compilation of these different constraints is reported in Figure 1, in what concerns the symmetry energy at saturation $X_0^{iv} = J$, and its slope $X_1^{iv} = L$. The tighter constraints are provided by nuclear theory, but it is interesting to observe that nuclear phenomenology gives independent uncertainty intervals for the empirical parameters that agree with the *ab-initio* modeling. Among the different parameter evaluations reported in Figure 1, the only one that is in principle fully model-independent is the one based on the parity-violation electron scattering measurement of the ^{208}Pb skin by the Lead Radius EXperiment (PREX) experiment [14]. This measurement seems to suggest values of J and L considerably higher than the other es-

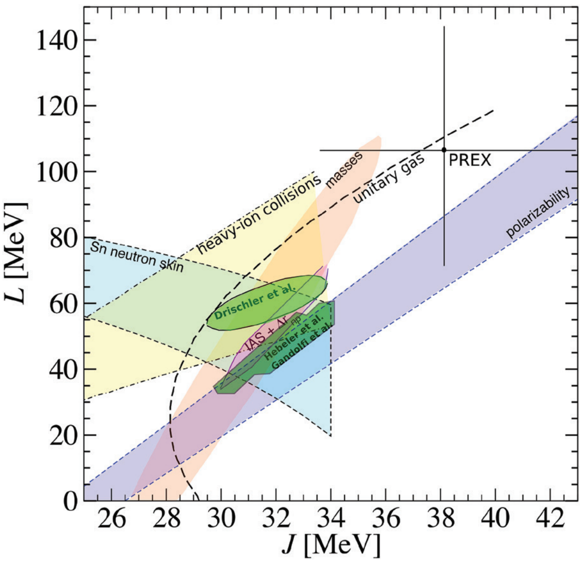

Figure 1. *Slope of the symmetry energy L versus the symmetry energy coefficient J, as extracted from different experimental and microscopic ab-initio theoretical constraints (see Ref. [6] for original references of the constraints).*

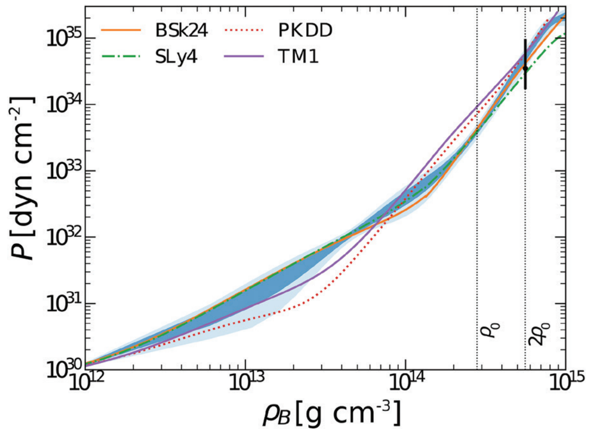

Figure 2. *Marginalized posterior for the pressure P versus baryon mass-energy density ρ_B. The blue dark (light) shaded region shows the 1σ (2σ) confidence intervals. Some popular nucleonic models are represented as lines. The vertical black bar corresponds to the constraint inferred from GW170817 in Ref. [5]. Figure adapted from Ref. [10].*

timations. However, the systematic errors are so large that no clear conclusion can be drawn at this stage.

If chiral effective field theory is today the most powerful constraint on the neutron-matter EoS, the role is inverted concerning the empirical parameters X_k^{is} characterizing symmetric matter. For those parameters, the precision of EoS measurement from the combined analysis of different nuclear experiments is remarkable. This is due to the fact that only nuclei between drip-lines can be probed in terrestrial experiments, and the properties of extremely neutron-rich nuclei are not yet fully explored. The lowest-order parameters, namely the saturation energy $X_0^{is} \equiv E_0$ and the associated saturation density n_0, are very precisely measured at the 2% level by nuclear mass and radii measurements, and the compressibility $X_2^{is} \equiv K_0$ is presently extracted at the 10% level from refined analyses of giant monopole resonance data.

All these different constraints can be incorporated in a nucleonic meta-modeling representation of the nuclear EoS, such as the one in Eq. (1) with the standard tools of Bayesian inference [9, 10]. To ensure that models are physically viable up to the extreme densities in the core of NSs, additional requirements are considered, namely the causality of the EoS and its capability of sustaining massive NSs (above 1.97 M_{sun}), like the precisely measured pulsar J0348+0432. The resulting most general EoS compatible with these constraints is represented in Figure 2. This estimation agrees with the constraint extracted from an agnostic analysis of the gravitational-wave event GW170817 [5], also reported in Figure 2. This shows a nice convergence between our micro- and macro-physics understanding of compact objects. We can also see that the knowledge on nuclear matter that can be extracted from laboratory experiments and *ab-initio* nuclear theory is very compelling, and it could be worthwhile to include it in future astrophysical data analyses to improve their predictive power. Some first studies, where the nuclear physics constraints are directly included in the data analyses, have started to be proposed [15]. It is also interesting to observe that several popular models currently used to interpret nuclear data fall outside the range of the posterior estimation of the pressure in Figure 2. This is because most nuclear models have been optimized to reproduce specific properties of nuclear data, notably in nuclear structure, where a very limited range of densities and isospin asymmetries are explored. Therefore, their extrapolation to beta-equilibrated very neutron-rich matter in a large-density domain might not be compatible with the combined set of constraints.

Are Non-Nucleonic Degrees of Freedom Excluded?

The unique hypothesis of the nucleonic meta-modeling is that the relevant degrees of freedom inside the core of a NS are given by protons and neutrons (supplemented by electrons and muons). In this respect, the EoS estimation of Figure 2 can be considered reliable, because it is reasonable to suppose that baryonic matter should be purely nucleonic up to around twice the saturation density. Although considerable uncertainty exists about the possible presence of hyperons in the core of NSs, the high mass of the lightest lambda hyperon imposes that the threshold density for its possible appearance be above about $2n_0$ [16].

Concerning the possible presence of deconfined matter, agnostic modeling of a first-order phase transition including constraints from LIGO/Virgo and Neutron star Interior Composition Explorer (NICER) data seems to exclude the possibility of a transition below $\sim 2n_0$ [17]. If we believe our nuclear physics constraints, the only possible scenario allowing a violation of the EoS in Figure 2 would be the absolute stability of quark matter, which, if true, would lead to the existence of pure quark stars [1, 18].

This shows the huge challenge connected to an increased precision of the measurement of the NS properties at moderate densities from future astrophysical observations.

The situation is different when we analyze observables that imply an integration over the whole density profile of the NS. For the mass–radius relation (Figure 3, upper panel), the parameter space compatible with nucleonic degrees of freedom is large, because densities as high as $\sim 6-8n_0$ can be reached in the core of the most massive NSs, and the associated EoS is dominated by the high-order empirical parameters $X_k^{is(iv)}$ (with $k>2$). Those parameters are virtually unconstrained by nuclear physics experiments, which probe densities close to saturation where their influence is too small, and low-order parameters dominate. Concerning *ab-initio* nuclear theory, the power counting associated with the diagrammatic expansion breaks down when the short-distance structure cannot be neglected, thus those calculations, although extremely powerful at low density, cannot be safely extrapolated beyond $\sim 1.5n_0$ [12]. These limitations of both nuclear theory and experiments lead to an increased uncertainty in the EoS at high density. Despite these large uncertainties, the nuclear physics prediction of the $M(R)$ relation is tighter than the present astrophysical measurements (see Figure 3). Combining the whole set of experimental and theoretical filters is definitely important for a reliable prediction of astrophysical observables.

In the case of the $M(R)$ relation, the hypothesis of nucleonic degrees of freedom implicit in the meta-modeling is certainly restrictive. Indeed, even if the exact location of the deconfinement transition toward quark matter is essentially unknown, if

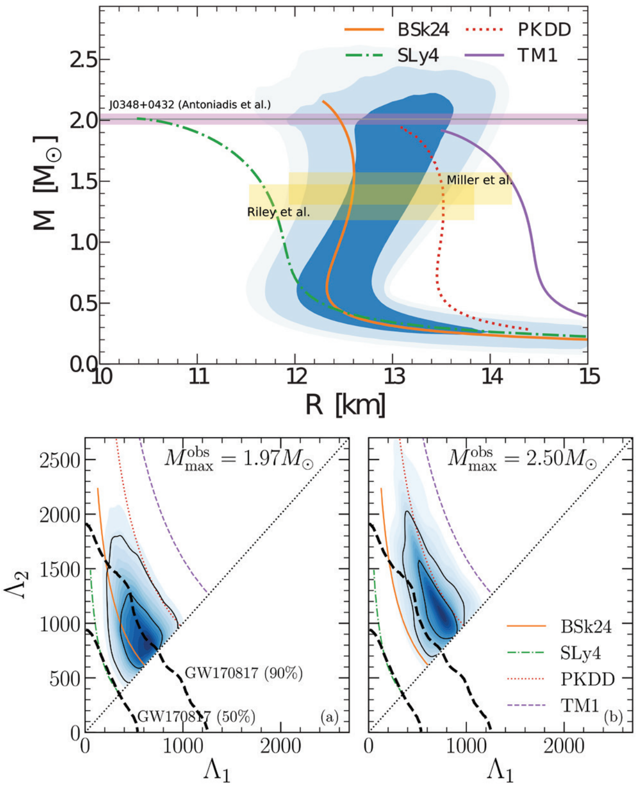

Figure 3. *Upper part: marginalized posterior for the NS mass–radius relation. The blue-shaded regions show the 68%, 95%, and 99% confidence intervals. Lower part: Marginalized posterior for the tidal polarizability parameter of the two components of GW170817. Dark (light)-shaded regions represent the 50% (90%) confidence interval with the Bayesian estimation; black dashed lines show the confidence regions as obtained in Ref. [5]. The left and right panels correspond to different constraints on the maximal NS mass. The results for the same popular EoS models as in Figure 2 are also represented. Figures adapted from Ref. [10].*

strange quark matter is not absolutely stable such a transition is expected at high density [18]. In particular, if this transition is strongly first order, the parameter space of the EoS increases, leading to a much larger spread of the possible $M(R)$ relation (Ref. [19] and references therein).

Because of the phenomenological nature of the effective models used for the quark phase, settling the parameter space associated with a phase transition to quark matter is a very hard task. However, the parameter space associated with the absence of such a transition is much more limited (see Figure 3). This means that the nucleonic meta-modeling can be used as a null hypothesis to set the existence of deconfined matter in the core of NSs, provided that the observations are sufficiently precise to challenge the nucleonic predictions.

The first steps in this direction come from the recent measurement of the tidal polarizability parameter Λ in compact binary mergers [5]. The compatibility of the posterior distribution of the Λ parameter shown in Figure 3 (lower left panel) with the LIGO/Virgo gravitational-wave measurement at the 90% level indicates that there is no compelling evidence that exotic matter is present in the NS core. However, the shape of the probability distribution predicted by low-energy nuclear physics constraints is very different from the one inferred from the GW analysis. New astronomical observations will hopefully produce more stringent constraints in the near future. For example, if a NS as massive as 2.5 $M_{\rm sun}$ were measured, this would lead to a clear incompatibility between the Λ measurement and the purely nucleonic hypothesis, as shown in Figure 3 (lower right panel), thus providing a more convincing evidence of the presence of deconfined matter in compact stars.

Future Constraints from Nuclear Physics Experiments

In the absence of such astrophysical evidence, an alternative path to challenge the nucleonic hypothesis would consist in putting more stringent constraints on the nucleonic meta-modeling prediction from improved laboratory measurements. A reduced error bar in the neutron skin measurement, such as that performed by the PREX collaboration [14], would greatly constrain the low-order empirical parameters in the isospin sector, thus allowing better extrapolations to higher density, and reduced uncertainties in the astrophysical predictions. The same is true for measurements from relativistic heavy-ion collisions, which are a unique experimental probe of densities of the order of $2n_0$. Only symmetric matter is probed in such experiments, but even a loose constraint on the higher-order parameter $X_3^{is} \equiv Q_0$ would greatly reduce the present uncertainty in the nucleonic extrapolation of the high-density EoS. Encouraging results in this sense have been recently presented by the High Acceptance Di-Electron Spectrometer (HADES) collaboration [20].

To conclude, even if the composition, properties, and degrees of freedom of ultra-dense matter such as can be found in the core of NSs is still largely unknown, we are presently facing an extremely exciting and rapidly evolving scientific epoch. For the first time, terrestrial nuclear experiments can be connected to astronomical observations, and it makes no doubt that, together with the amazing recent progress of *ab-initio* theoretical modeling, they will further contribute in a next future to unveil the remaining mysteries in the properties of matter under extreme conditions.

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A Dedicated Laser-Polarization Line at ISOLDE

The spin-polarization in unstable nuclei leads to anisotropic emission of their decay radiation and to angle-dependent cross-sections in nuclear reactions. The details of the decay anisotropy depend on the type of radiation, the involved nuclear states, and the nearest neighbors of the nucleus, after its implantation in a host material [1].

Over the past decades, a variety of techniques have been explored to achieve spin-polarization in unstable nuclei. These techniques are often directly related to the production process of the radioactive isotope of interest (e.g., when the spin-orientation is induced by the pick-up of polarized neutrons, or in projectile fragmentation, transfer, fusion-evaporation, or coulomb excitation reactions (see [17] and references therein). These methods are element independent, but they are mostly applicable for nuclei not too far from stability or lead to a rather low amount of spin-polarization. Alternatively, unstable isotopes can be polarized after production, using, for example, element-specific laser optical pumping of low-energy beams, leading to high degrees of nuclear spin-polarization, as shown for several alkali (Li, Na, K, Rb, Cs) and alkali–earth (Be, Mg) elements, and even the noble gas Ar.

The scientific questions that can be addressed with polarized unstable nuclei combined with the different ways to produce polarization make such nuclei interesting for a range of fields, as shown in Figure 1. These range from the studies of the fundamental symmetries [2], through nuclear structure [3] and nuclear astrophysics [4], all the way to material science [5], and, more recently, chemistry and biology [6], and even medicine [7]. This variety of research topics that can profit from spin-polarized radioactive beams motivates the need for more nuclear-spin polarization setups.

Here we describe a new experimental beam-line dedicated to laser-polarization and versatile studies with polarized short-lived nuclei [2, 8, 9]. It is located at the Isotope Mass Separator On-Line (ISOLDE) facility at the European Council for Nuclear Research (CERN), which already has a long track record in spin-polarizing unstable nuclei. The COLLAPS collaboration has used the optical pumping in many nuclear-structure studies (e.g., Refs. [3] and [10]) and several material-science studies since the 1980s. The first tests of biological studies were also performed here [11]. The NICOLE experiment [12], active until about a decade ago, used low-temperature nuclear orientation to investigate nuclear structure and fundamental interactions. Furthermore, polarization of a reaccelerated beam using passage via tilted foils was tested behind the Radioactive Beam Experiment (REX)–ISOLDE in 2012 [13]. The polarization-beam-line presented here, commissioned in 2016 [8], used for research since 2017 [2, 9], and presently undergoing upgrades, is the newest ISOLDE beam-line of this type, and it is entirely devoted to studies with laser-polarized short-lived nuclei. The polarization section can be coupled to different end-stations, which are tailor-made to distinct scientific questions. For example, one of the existing end-stations is devoted to the very sensitive beta-detected Nuclear Magnetic Resonance (β-NMR), which can be also used as a diagnostic tool, to optimize and determine the degree of spin polarization achieved in the optical pumping process.

Optical Pumping to Achieve Nuclear Spin-Polarization

Laser polarization of nuclear spins can be described as two linked processes: direct polarization of atomic electrons and transfer of atomic polarization to the nuclei via the hyperfine interaction (both atomic and nuclear

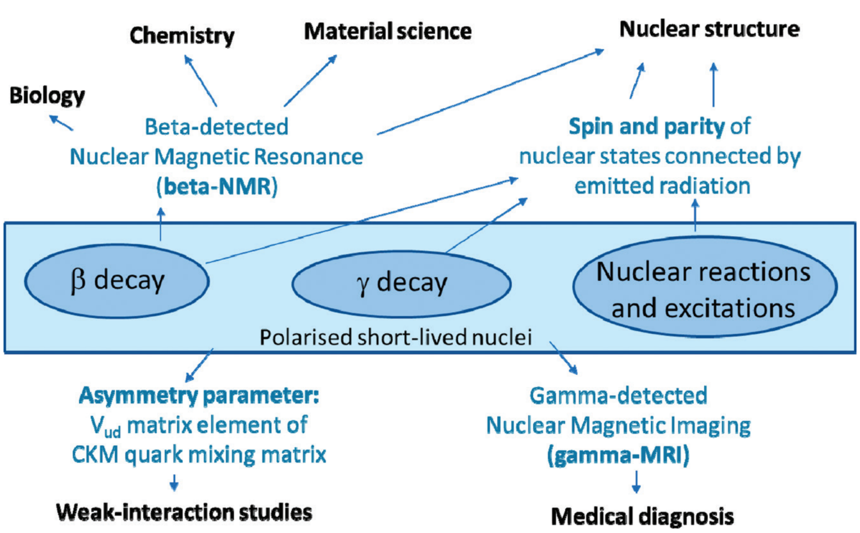

Figure 1. *Selected research topics with spin-polarized unstable nuclei.*

spins should be different from 0). The laser-atom/ion interaction has to take place in a weak magnetic field, which provides a quantization axis and allows the electron (J) and nuclear (I) spins to remain strongly coupled (leading to hyperfine sublevels described by the quantum number $F= |I-J|, \ldots |I+J|$). The laser light is circularly polarized (either left- or right-handed), so that it can transfer angular momentum to the electron that is being excited. Ideally, a closed excitation loop is used, in which the resonantly excited electron decays back to its initial state. In such a case, the polarization can be efficiently built up due to multiple excitation–deexcitation cycles, each of which brings one quantum of angular momentum. An example of a pumping scheme is shown in Figure 2. Here, circularly polarized laser light triggers transitions from the hyperfine sublevel with $F = 2$ to the excited-state sublevel with $F' = 3$, marked by red arrows. Selection rules for excitation and spontaneous decay require that m_F increases by 1 for the excitation, and change by −1, 0, 1 for the spontaneous decay. Because multiple excitations take place one after another, in the end, up to 100% of the population can be transferred in the magnetic substate with largest m_F ($m_F = 2$ in the example), meaning the maximum degree of (atomic) polarization is reached. Allowed decay to other atomic states, not enough excitation cycles, or other sources of polarization loss lead to occupation of other m_F levels, thus lowering the polarization. Because optical pumping requires several excitations, the laser power needs to be higher (usually dozen(s) to hundred(s) of mW) than for optically detected collinear laser spectroscopy employed very often at ISOLDE (down to mW).

Since the process profits from a closed excitation-decay scheme, it is the most efficient and easiest for atoms or ions with one valence electron, which have a simple level structure. This is the case for alkali atoms and singly charged alkali–earth ions. It is also possible to find suitable transitions in other chemical elements, especially when pumping from excited states is considered, which was done recently. The atomic polarization builds up after a dozen excitations, which is extremely fast due to the lifetimes of the involved excited atomic states, which are in the range of tens to hundreds of ns. Thus, within less than a microsecond the atomic spins reach a steady-state polarization. In the process, the nuclear spin is also polarized, through the hyperfine interaction. This nuclear-spin polarization leads to spatial asymmetry in β or γ emission that is then used in different ways in various fields of research [1].

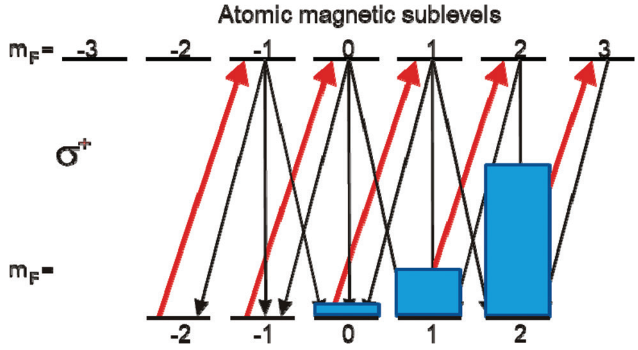

Figure 2. *Optical pumping (shown by red and black arrows) between hyperfine sublevels $F = 2$ and $F' = 3$ in the presence of a very weak magnetic field that provides the quantization axis. As a result, the population of the magnetic sublevels (blue bars) shifts to higher m_F and atomic-spin polarization is created. For details, see text.*

Experimental Setup

The laser-polarization beam-line, as it was used at the end of 2018, just before CERN's long-shutdown (LS2), is shown in Figure 3. The spin-polarization part starts with a region where the laser and ion beam are overlapped, by deflecting the ion beam horizontally by five degrees, allowing for its overlap with the laser light that enters the setup through a small window centered at the beam axis. Next comes a chamber hosting the Doppler-tuning electrode and the beam neutralization cell. A variable voltage is applied to the former, so that the energy of the ion beam is gradually changed as the beam passes through it. The latter is used to neutralize the radioactive ion beam in flight through charge-exchange collisions with an alkali–metal vapor (usually sodium or potassium, depending on the element to be neutralized). The cell is set to the same potential as the end of the Doppler tuning electrode, so that the atoms that leave it are in resonance with the laser light and can be thus optically pumped. The cell is heated to over 200°C so that the metallic sodium or potassium are vapourized and can neutralize the beam without obstructing its way. Behind the neutralization cell, a set of two photomultipliers (PMs) can collect immediate fluorescence, which is used to tune the laser on resonance with an intense beam of atoms of the elements of interest. The following optical-pumping section is a two-meter-long tube in which the

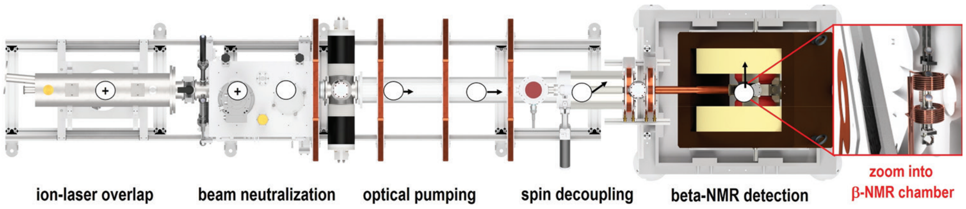

Figure 3. *Laser-polarization setup at ISOLDE, as used before CERN LS2 (adapted from R. Harding et al. [9]). Inset: inside the β-NMR measurement chamber. See text for details.*

laser light excites multiple times the atoms and where the spin-polarization is built up. The tube is surrounded by 1-m diameter Helmholtz coils creating a longitudinal magnetic field of about 20 Gauss that provides the quantization axis for the optical-pumping process and is used to guide and maintain the spin polarization along the beamline. For optical pumping on ions instead of atoms (being implemented during LS2), the optical-pumping tube is set at the same potential as the Doppler-tuning section and the empty neutralization cell.

The next beam-line elements can be already considered as part of one of the end stations devoted to different scientific questions. Shortly before CERN's LS2, the end-station installed was used to performing β-NMR studies in liquids, motivated by several topics in chemistry and biology. This setup (Figure 1) starts with a set of coils that provide an increasing magnetic field, used for turning the atomic spin ensemble adiabatically toward a strong magnetic field that is oriented perpendicular to the beam axis, thus orienting the atomic (and nuclear) spin-orientation axis along the strong field direction. This 1.2-T electromagnet hosts between its poles a vacuum chamber that is directly connected to the beamline, and which contains a movable sample holder. Once the atoms reach a high magnetic field regime and/or are implanted in the host material, the hyperfine interaction is no longer active, and the nuclear spins are now coupled to the strong magnetic field. Depending on the probe-host material combination, the nuclear polarization can be maintained for long enough to perform measurements of the asymmetric β-decay. The sample holder can hold one of several samples, either a 10–20 µl liquid deposited on its surface, or a crystal, and the host of interest can be placed in the middle of the chamber using a mechanical feedthrough. A coil surrounding the central position is used to resonantly excite the nuclear spins using radio-frequency radiation (in the order of MHz). Next to it, there is a much smaller rf coil around a vacuum-tight vial that contains water (see inset in Figure 1), which is used as a ^{1}H NMR reference probe to actively stabilize the static magnetic field to better than 1 part-per-million (ppm) level over a period of several days through a feedback stabilization loop. Between the chamber and the magnet poles, there are two sets of two thin plastic scintillators coupled to very small and light Si PMs, to detect the asymmetry in the number of β particles emitted parallel and antiparallel to the spin-orientation (and magnetic-field) direction. Between the detectors and the magnet poles there is enough space for Printed Circuit Board (PCB) shimming coils that improve the homogeneity of the magnetic field around the probe to between 1 and 5 ppm in all three directions. The above experimental setup allows one to check the degree of created nuclear-spin polarization and it is used for β-NMR studies in solid and liquid samples [9].

Examples of Ongoing Studies

The ISOLDE laser-polarization line aims at addressing many of the versatile research topics shown in Figure 1. Below, we present briefly the first results for several studies, which have been already published. Other ongoing research projects involve liquid β-NMR studies of the alkali–metal interaction with DNA G-quadruplex structures (led by B. Karg and M. Kowalska [6]) and β–γ-neutron correlations studies in the decay of astrophysically relevant neutron-rich nuclei around ^{132}Sn (led by M. Madurga [4]).

Laser-Polarization of a Noble-Gas Isotope ^{35}Ar

The successful laser-polarization of ^{35}Ar was the first scientific achievement reached at the laser-polarization line. Polarizing a ^{35}Ar beam, which is very challenging with the method of optical pumping, is highly relevant for the study of the V_{ud} matrix element of the Cabibbo Kobayashi Maskawa (CKM) quark mixing matrix [14]. While the V_{ud} matrix element is mostly studied via 0^{+} to 0^{+} Fermi β-decay, it has been shown [15] that mirror β-decays, like that of ^{35}Ar to ^{35}Cl (Figure 4, left), can also be a sensitive probe. For this, one needs to know the ratio ρ between the total Fermi and Gamow-Teller strengths in the specific mirror transition, in addition to the mass difference, lifetime, and branching ratio for the mirror transition. This ratio ρ can be derived from the measured β-decay asymmetry A_β in the considered decay branch, and of all mirror decays, that of ^{35}Ar has been identified as the most sensitive for such study. To deduce a V_{ud} value that is competitive to other studies, a relative precision of 0.5% in the measured β-decay asymmetry is required. To achieve this, first an acceptable level of nuclear-spin polarization for ^{35}Ar had to be established. We employed for the first time the optical pumping with three laser frequencies, to enhance the induced spin polarization in the ^{35}Ar atom beam. Simulations of single and multiple laser-induced polarizations, compared to the observed relative peak intensities in the β-asymmetry observed through the hyperfine structure, hinted at close to 100% polarization of atomic spins (Figure 4, right). Unfortunately, the absolute degree of β-decay asymmetry pointed to a nuclear polarization that was of an order of magnitude lower [2], which must be due to the loss of nuclear spin-polarization at several stages of the process. Further studies are needed to investigate this. For the final measurement, one will need to know very well the degree of nuclear-spin polarization. This determination can be done by using as a reference another β branch with known β-decay asymmetry factor, which can be distinguished from the interesting transition (e.g., by a coincidence with a subsequent γ ray). ^{35}Ar has such a decay channel, with $A_\beta = 1$ and 1% branching ratio, which is followed by a prompt γ ray of 1219 keV. The final setup will therefore need to combine a compact magnet with β and γ detection, allowing the tagging of β particles with the 1219 keV γ rays.

Determination of the Magnetic Moments of Short-Lived Nuclei with ppm Accuracy

Shortly before LS2, at the end of 2018, we implemented several novel technical solutions into our β-NMR end-station as part of a European Research Council (ERC) project, and we combined these technical upgrades with *ab initio* quantum chemistry calculations. This has allowed us to determine for the first time the magnetic moment of a short-lived nucleus with ppm accuracy, which is an improvement of two orders of magnitude compared to the literature [9]. This result was achieved for the 1.1 s half-life ^{26}Na, which is relevant to biochemistry studies. A vacuum-compatible *in-situ* ^{1}H NMR probe allowed us to calibrate and stabilize the magnetic field at a sub-ppm level. This probe also eliminated the need for additional β-NMR reference measurements on ^{26}Na in another host. New *ab initio* calculations of NMR shielding values (i.e., the effect of the closest environment of the magnetic field felt by the probe nucleus) for Na in different hosts allowed improving the accuracy of the reference magnetic moment for the stable ^{23}Na, thus removing a large systematic error due to old NMR shielding corrections. In addition to improving the accuracy of the magnetic moment of ^{26}Na to the ppm level, we were able to also improve the accuracy of the magnetic moments of $^{27–31}$Na from several dozen to a few hundred ppm, because the ^{26}Na moment had been used as their reference in earlier studies. Our approach to determine accurate magnetic moments of short-lived nuclei can be extended to many other β-NMR-compatible nuclei. One of the first possible applications of this improvement in accuracy is the determination of the neutron distribution in halo nuclei, based on the so-called hyperfine anomaly that can be derived from an accurate magnetic moment combined with an accurate hyperfine structure measurement. The other field of application concerns chemistry and biology studies using liquid β-NMR, for which we have established now a universal referencing scheme that links β-NMR directly with conventional NMR and quantum-chemistry calculations, as described in the next paragraph.

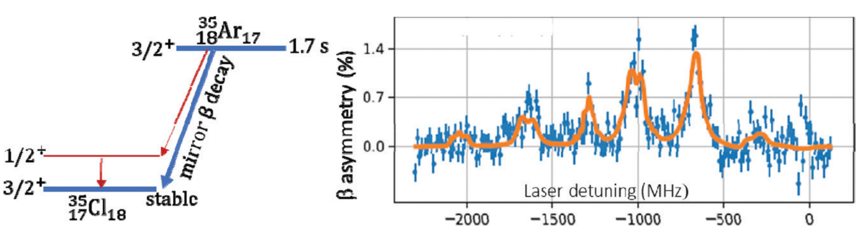

Figure 4. *Mirror decay of ^{35}Ar to ^{35}Cl (left) and β asymmetry created after optical pumping scanned through the hyperfine structure of ^{35}Ar (right, adopted from Gins et al. [3]).*

Universal Referencing for β-NMR in Liquids and Direct Connection to Conventional NMR

The combination of accurate magnetic moments of short-lived β-NMR nuclei with the *in-situ* NMR measurement on a stable isotope, such as ^{1}H in water, opens the path for a very interesting universal β-NMR referencing scheme. The scheme makes redundant reference measurements in *ad-hoc* β-NMR hosts, which are often not the same ones as those used

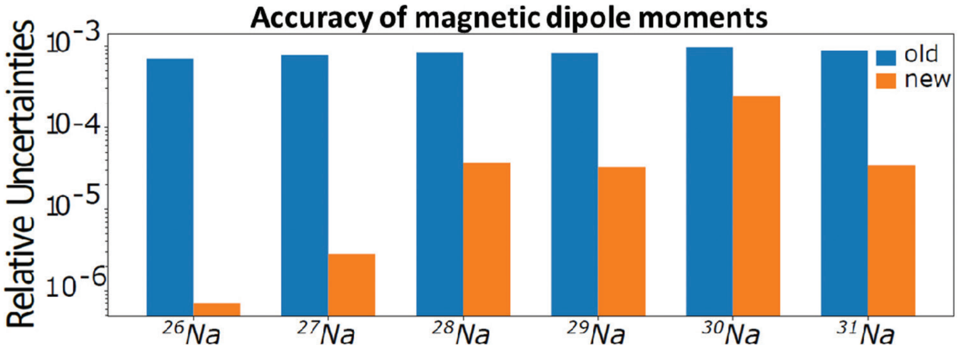

Figure 5. *Accuracy in the magnetic moments of* $^{26–31}$*Na before and after our studies.*

in conventional NMR. Even more importantly, the shift in the resonance frequency due to the influence of the immediate environment of the probe nucleus, which is key for chemistry and biology applications of NMR, can be quantified in absolute terms (NMR shielding) instead of relative terms (chemical shift; i.e., a difference to a reference compound). Finally, the determined NMR shielding can be directly compared to the shielding obtained in conventional NMR and to quantum chemistry calculations that are in any case performed in the absolute scale. One of the first applications of this scheme will be our upcoming studies of the interaction of sodium and potassium ions with DNA G-quadruplex structures [6].

Beam-Line Status and Ongoing Upgrades

During LS2, extensive upgrades on the polarization and end-station sides are ongoing [16], with the aim to finalize most of them by the beginning of the 2021 running period. The polarization line will be extended to host additional beam-focusing elements and better beam diagnostics. Insulated electrodes will be added also inside the optical pumping region, allowing for the optical pumping of ions. In 2021, work will start on new polarization schemes for potassium and a new control system will be implemented.

Within the end-station for liquid β-NMR, the 1.2 T electromagnet is being changed for a 4.7 T horizontal superconducting magnet with its field along the beam axis, providing field homogeneity and medium-term stability better than 1 ppm, as well as resulting in a four times higher NMR spectral resolution. The implementation of this magnet requires a totally new β-NMR section, from the sample holders, via rf coils, all the way to β detectors. This upgrade will be crucial for an even higher resolution of biological β-NMR and will be useful for β-NMR studies relevant to nuclear structure and material science.

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The TRIUMF UltraCold Advanced Neutron Source

Introduction

A new ultracold neutron (UCN) source is being developed at TRIUMF for fundamental physics experiments. The TRIUMF UltraCold Advanced Neutron (TUCAN) Collaboration seeks to measure the neutron electric dipole moment (EDM) to the precision $\sigma(d_n) = 1 \times 10^{-27}e$cm. The collaboration members are mostly from Japan and Canada.

The neutron EDM is important to measure because it provides a constraint on the violation of time-reversal symmetry, and therefore on the violation of particle–antiparticle symmetry (charge-parity, or CP violation). As a result, the neutron EDM can shed light on the strong CP problem, which is related to the prediction of axions, the supersymmetry (SUSY) CP problem, and new CP-violation at the TeV scale, and baryogenesis scenarios such as modifications to electroweak baryogenesis [1]. The best measurement of the neutron EDM is consistent with zero, with an experimental upper bound of $d_n < 1.8 \times 10^{-26}e$cm (90% C.L.) [2]. The TUCAN EDM experiment would provide an order of magnitude improvement. Several competing experiments are pursued worldwide that aim for the same level of improvement in the next few years [3]. In this article we describe progress on the TUCAN project, and its uniqueness. The principal uniqueness and competitive advantage for TUCAN is that we use a spallation-driven neutron source, coupled to a superfluid helium (He-II) production volume for the UCN. Other experiments use a reactor source of neutrons rather than spallation, or solid ortho-deuterium for the production volume, both of which come with significantly different optimizations and challenges. We anticipate that our solution will be successful in significantly increasing the number of UCN delivered to experiments beyond the capabilities of existing sources.

The TUCAN facility is being developed with the capability of supporting two experiments conducted in tandem. While the immediate goal of the collaboration is to complete a world-leading measurement of the neutron EDM, the long-term goal is to create a UCN user facility at TRIUMF that could be exploited for a variety of experiments. A new measurement of the neutron lifetime or of quantum states of neutrons bound by gravity are examples of experiments that could be improved with the increased neutron flux offered by the TUCAN source.

Facility at TRIUMF and Prototype UCN Source

Over the past several years, a UCN production facility has been constructed at TRIUMF, based on a prototype superfluid helium cryostat. The proton beam extracted from the TRIUMF cyclotron is diverted by a new kicker magnet [4] into a new proton beam-line [5] that ends with a water-cooled tungsten spallation target. Beam delivery to the spallation target has now become a routine process. The design proton beam current for the beam-line is 40 µA. We have operated the beam-line at currents up to 10 µA and are now in the process of certifying it for operation at 40 µA.

The prototype (“vertical”) UCN source is located above the spallation target, which is normally driven with proton beam currents of 1 uA. Steel and concrete radiation shielding surrounds the apparatus. An arrangement of Pb, graphite, and heavy water is used to reflect and moderate the neutrons. A portion of the heavy water is cooled to 20 K, serving as a cold neutron moderator. Cold neutrons of kinetic energy 1 meV entering the superfluid helium volume may be downscattered by producing phonon waves, coming nearly to rest, and thereby becoming ultracold (kinetic energy < 300 neV). Higher-energy cold neutrons can downscatter to become UCN through multiphonon/roton excitations. The superfluid helium is cooled to ~ 1 K, far below the superfluid transition, to suppress UCN losses. A schematic diagram of the vertical source is shown in Figure 1. The proton target is routinely irradi-

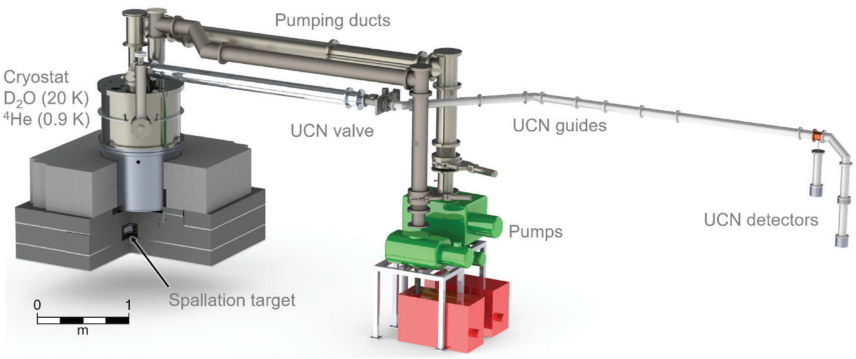

Figure 1. *The vertical UCN source as installed at TRIUMF (radiation shielding removed for clarity). The function of the source in this arrangement is described in the text and in Ref. [5].*

ated for a period of 60 s, during which the UCN density builds up. After irradiation, a valve is opened and UCN are transported to experiments located outside the radiation shielding.

In November 2017, the vertical source was used to characterize the production of UCN from the source and the lifetime of UCN in the superfluid helium [6]. During an extensive test campaign in November 2017, we extracted up to 325,000 UCN after a one-minute irradiation of the target (Figure 2), over three times more than previously achieved with this source when it was used at the Research Center or Nuclear Physics in Osaka (RCNP Osaka). The corresponding ultracold-neutron density in the whole production and guide volume (60.8 liters in total) was 5.3 cm^{-3}. The storage lifetime of ultracold neutrons in the source was initially 37 s and dropped to 24 s during the 18 days of operation, a change that we ascribe to cryopumping of contaminants into the source volume. During continuous irradiation of the spallation target, we were able to detect a sustained ultracold-neutron rate of up to 1,500 s^{-1}. Simulations of UCN production, UCN transport,

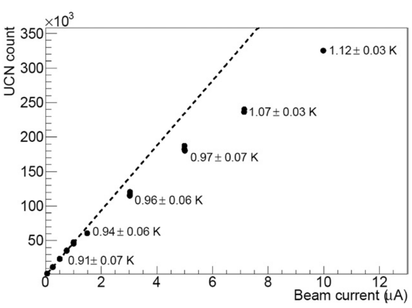

Figure 2. *UCN counts as a function of beam current for a 60-second-long irradiation of the spallation target. The future UCN source upgrade will have both a steeper slope, and be more linear with beam current, being designed to handle a beam current of 40 μA.*

temperature-dependent UCN yield, and temperature-dependent storage lifetime showed excellent agreement with the experimental data, confirming that the UCN upscattering rate in superfluid helium was proportional to T^7.

Month-long experimental campaigns were also carried out in late 2018 and late 2019. These experiments focused on improved thermometry for the UCN source and better temperature control, and UCN storage and transport experiments, including those involving polarized UCN. The experiments served as critical research and development (R&D) toward the upgrades to the UCN source, and the neutron EDM experiment.

Planned Upgrades, Their Impact, and Recent Progress

An overview of the facility planned at TRIUMF is shown in Figure 3, showing both the TUCAN source and EDM experiment. The upgraded UCN source will feature a more horizontal geometry, where UCN will be produced in a bottle, then exit horizontally, passing through a small vertical chicane that keeps the 1 K He-II held in the production volume by gravity. The horizontal geometry increases the UCN transport efficiency from the source to the experiment. The horizontal length of He-II also locates the main cryostat further from the radiation produced in the spallation target, which is a superior solution to avoid radiation damage for long-term operations.

The cryostat has been upgraded to handle the full 40 μA design beam current. Heat transport from the production volume, located above the spallation target to the cryostat, located 2.5 m away, is accomplished through a 15-cm-diameter horizontal tube filled with He-II through which the UCN also pass. Heat transfer is done through an 0.6-m-long Cu heat exchanger with the 3He coolant in the cryostat. This is a novel solution for the heat exchanger that is necessitated by the ~10 W of heat that will need to be removed when the beam is switched on. Over the past several years we have conducted R&D to show that the UCN requirements and heat exchange requirements can be compatible for this heat exchanger.

We completed a full optimization of the cold moderator system for the new source [7]. The main feature is an LD_2 cold moderator, with the LD_2 being circulated by a thermosyphon. In all, the UCN production rate will be 1.6 x 10^7 s^{-1} at 40 μA current. The EDM experiment cells (2 x 30 L) will be filled with about 20 million UCN by each beam pulse (a beam pulse is minutes in length). The beam is then switched off for the EDM experimental cycle (again requiring several minutes). At the end of the cycle, about 2 million UCN will be detected, including storage and transport losses and detection efficiency. Repeating this cycle over the course of 400 days, a statistical uncertainty of 1 x $10^{-27}e$cm will be reached for the neutron EDM. The EDM experiment itself will be discussed momentarily.

The facility will also be arranged as a multiuser facility. A second UCN port will initially be used to test UCN transport and storage components for the EDM experiment. Once the EDM experiment use is complete, we plan to make it available to users through TRIUMF's Experiments Evaluation Committee.

The He-II cryostat is based on a ^{3}He refrigerator, the construction of which was completed in April 2020 (Figure 4). The cryostat was successfully cooled to 1.23 K in September 2020, using natural helium as the cryogen. Tests of the Cu heat exchanger will be ongoing through spring 2021. The cryostat will then

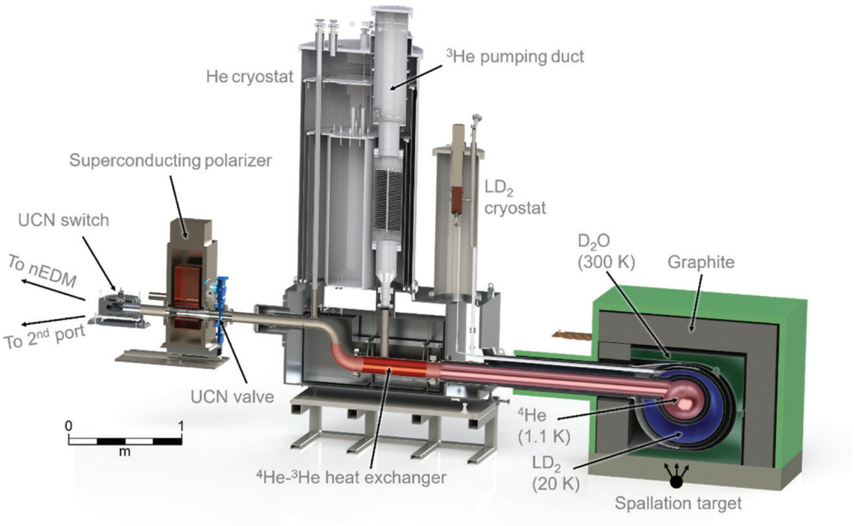

Figure 3. *Schematic diagram showing the TUCAN source after the completion of the upgrade. Elements of the upgrade are described further in the text.*

be shipped to TRIUMF for installation and testing with ^{3}He cryogens and larger pumps (see Figure 3), which should achieve sub-1K cooling at higher powers.

The UCN production volume is an Al vessel, coated with nickel plating for UCN compatibility. This vessel will be characterized with UCN and then integrated into the source cryostat system. The construction of the vessel is nearing completion at TRIUMF.

Neutron EDM Experiment

The TUCAN EDM experiment (Figure 5) is a room-temperature EDM experiment. Neutrons from the source are polarized in a superconducting magnet and transported to dual measurement cells located in a homogenous magnetic field B_0. The magnetic field is carefully tailored with coils and the experiment housed within a magnetically shielded room to reduce magnetic noise. A central electrode provides a strong electric field (12 kV/cm) aligned parallel or antiparallel to B_0. Surrounding alkali atom magnetometers and a ^{199}Hg comagnetometer monitor the field around and in the measurement cells. An AC coil tilts the spins of the neutron into the horizontal plane with a $\pi/2$ pulse that initiates free precession. After a period of 150 s, a second $\pi/2$ pulse, in phase with the first, is used to analyze the phase accrued by the neutrons relative to the AC frequency. In this way a precise determination of the neutron precession frequency is made; a nonzero EDM would show up as a frequency shift when the direction of the electric field is reversed relative to the direction of B_0. The neutron spins are analyzed by adiabatic transport to spin-sensitive neutron detectors (simultaneous spin analyzers).

Some unique features of the EDM experiment are: the use of a self-shielded B_0 coil, to reduce coupling to the surrounding mu-metal shielding; alkali atom magnetometers based on nonlinear magneto-optical rotation [8];

Figure 4. *Preparation and installation of the He-II cryostat at KEK for testing. Left: cryostat internals. Right: nearing completion of assembly.*

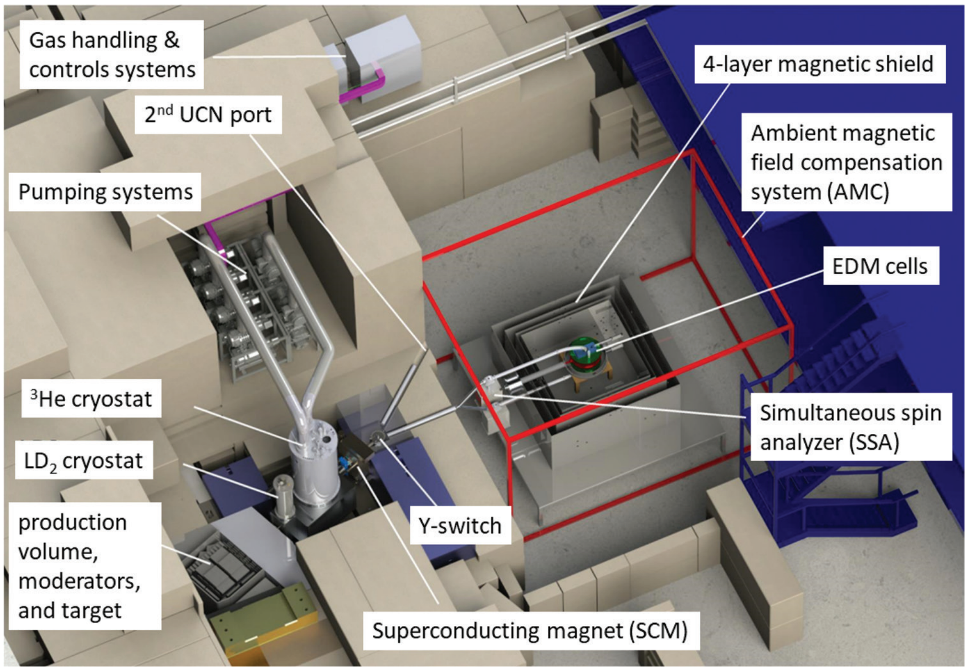

Figure 5. *View of the upgraded TUCAN source (left), and neutron EDM experiment (right) in the area at TRIUMF, shielding blocks partly removed for clarity. The layout is described further in the text.*

and a future upgrade involving simultaneous $^{199}Hg/^{129}Xe$ comagnetometry, which is being developed [9]. Of course, the principal unique feature is the spallation-driven He-II UCN source, which will deliver unprecedented numbers of UCN to the experiment.

In 2021–2022, the UCN source upgrade will be installed, commissioned, and characterized, both cryogenically and in its UCN production capabilities. In 2022, the magnetically shielded room will be installed at TRIUMF. This will enable precision magnetometry experiments to be conducted locally at TRIUMF for the first time. In 2023, the EDM experiment will be constructed and commissioned, to be followed by data taking. To reach the full statistics of the EDM experiment, a helium liquefaction upgrade at TRIUMF will be necessary. As stated earlier, a statistical precision of 1 x 10^{-27}*e*cm would be achieved in around 400 days of running. Once the EDM experiment is operating, we plan to consider other experiments that could be done at the second experimental port. We expect this will lead to a fruitful suite of physics experiments that will be performed using the TUCAN source.

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The NUMEN Project: Shedding Light on Neutrinoless Double Beta Decay by Heavy-Ion Nuclear Reactions

Introduction

Beta decay is one of the first observed [1] and, to date, most studied phenomenon in subatomic physics. It is a spontaneous process occurring in atomic nuclei composed of particular arrangements of protons and neutrons that make them unstable under the release of a beta particle (an electron) or an anti-beta particle (a positron). In the final state the "parent" nucleus is transformed into a "daughter" one containing one proton (neutron) more and one neutron (proton) less. A very light neutral particle, named neutrino [2], characterized by $1/2\hbar$ intrinsic angular momentum, is contextually generated, guaranteeing the respect of all known symmetry laws. In some very rare cases, double beta decay can occur [3, 4], where two neutrons (protons) inside a nucleus simultaneously transform into protons (neutrons), releasing two electrons (positrons) plus two antineutrinos (neutrinos).

In our current understanding of particle physics, defined by a set of rules known as the Standard Model, there are several fundamental quantities that need to be conserved in every process. One of them is the "lepton number." Leptons are a family of fundamental particles that include positrons and electrons, along with the aforementioned chargeless neutrinos. Since electrons are "matter" and positrons "antimatter," the Standard Model dictates that during beta decay, they must be released alongside either an antineutrino or a neutrino, respectively. However, since neutrinos are neutral, the distinction with their antiparticles is not so direct, as pointed out by Majorana [5]. For a long time the neutrinos were believed to rotate anticlockwise compared to the direction of their motion (left-handed), with the opposite behavior for antineutrinos (right-handed), thus offering a physical way to unambiguously distinguish them [6]. However, this property only holds if neutrinos move at the speed of light, and consequently if they are massless. Nowadays we know that this is not the case, as demonstrated from recent neutrino oscillation experiments [7], so neutrinos could in principle be their antiparticles or, in other words, be "Majorana" particles. We should recall here that neutrino oscillation experiments are sensitive only to mass differences between neutrino species, giving no answer about the absolute value of these masses. The neutrino mass ordering is also untouched by oscillation experiments, leaving the possibility that electron neutrinos are the lightest (normal mass hierarchy) or the heaviest (inverted hierarchy).

In this framework, another type of beta decay, the "neutrino-less double beta" ($0\nu\beta\beta$-decay), was predicted a long time ago [8]. In the $0\nu\beta\beta$-decay, two beta particles are emitted, but no neutrino, since the two generated neutrinos "annihilate" each other. If observed, this still hypothetical process would appear to violate lepton number conservation, giving a manifestation of physics beyond the Standard Model. In addition, the observation of this process would prove for the first time that neutrinos are their own antiparticles, as predicted by Majorana, and would make it possible to extract their absolute masses. $0\nu\beta\beta$-decay predicted rates are also sensitive to the neutrino mass ordering and could disentangle normal from inverted hierarchy scenarios, with a major impact in particle physics and cosmology. Moreover, if observed, $0\nu\beta\beta$-decay will signal that the exact balance between matter and antimatter can be violated in nature. The observed disparity in the enormous amount of matter compared with antimatter in the known universe is currently one of the biggest problems faced by physicists.

The direct confirmation that $0\nu\beta\beta$-decay can occur would, therefore, be a big deal for nuclear physics, particle physics, and cosmology, potentially providing the tools to make a significant step forward in our comprehension of the fundamental laws of the universe.

Open Problems on $0\nu\beta\beta$-Decay Research

Extending our understanding of the most fundamental building blocks of the world around us is, understandably, a strongly motivating prospect for physicists. This has meant that the hunt for $0\nu\beta\beta$-decay has ramped up in recent years. Even though $0\nu\beta\beta$ events have not been reported so far, there is a strong competition, involving large scientific collaborations and international laboratories in the fields of neutrinos, and nuclear and particle physics, to detect it.

Physicists have proposed a variety of methods to infer the extremely long half-life for the $0\nu\beta\beta$ process (more than 10^{16} times longer than the life of universe!) or, better to say, the extremely low decay rate expected with the most sensitive experimental facilities (few counts per ton of radioactive material per year, at most). Since $0\nu\beta\beta$-decay involves transitions in atomic nuclei, nuclear structure aspects are essential to quantitatively describe it. In particular, the key quantity is the so-called nuclear matrix element (NME), which expresses the probability amplitude that the initial nuclear state, represented by the parent nucleus in its ground state, can be transformed into the final state of the daughter nucleus, under the action of the weak interaction operators, as the result of 0νββ-decay.

Differently from the decay rates, NMEs are not observables and can only be determined by calculations. Based on state-of-the-art theories, physicists worldwide are now aiming to evaluate the NMEs that control the 0νββ-decay rate with a higher and higher degree of complexity. However, these calculations are faced with significant challenges in providing the high level of precision required, due to the intimate many-body nature of the involved nuclear states.

Despite the tremendous efforts and improvements achieved by nuclear structure studies, the ambiguities in the present models are still too large to provide NMEs with the necessary accuracy. In this context, the "Nuclear Matrix Elements for Neutrino-Less Double Beta Decay" (NUMEN) Project [9] is aiming to provide, for the first time, key experimentally driven information from nuclear reactions, with the help of cutting-edge facilities based at the Italian Institute for Nuclear Physics (INFN) Laboratori Nazionali del Sud (LNS) in Catania. A synergic project, "Nuclear Reactions for Neutrino-Less Double Beta Decay," funded by European Research Council, is also moving along this research line. The Superconducting Cyclotron accelerator (CS) and the MAGNEX large acceptance magnetic spectrometer [10] are the main tools driving this research. These devices are shown in Figure 1 and Figure 2. The CS accelerates the heavy-ion beams at energies in the range of 10 to 60 MeV/u (where the nuclear reactions of interest are expected to occur with the largest probability) with the required high resolution and low emittance, and MAGNEX detects the reaction products with large acceptance and high resolution in mass, energy, and angle, guaranteeing a high sensitivity to rare processes.

An Interesting Analogy

Double beta decays are not the only processes in physics where the electric charge of a nucleus is changed by two units being the global number of protons plus neutrons unchanged. Other *double charge exchange* (DCE) processes, driven by the strong interaction and manifesting in pion [11] or heavy-ion induced collisions are far easier to observe than 0νββ-decay. Just to have an idea, the coupling constants of the strong interaction are of the order of 10^7 times larger than those governing the weak interaction and these factors enter to their fourth power in the transition probabilities for DCE reactions and 0νββ-decays. An interesting aspect of the DCE reactions is that they probe the same nuclear states of the parent and daughter nuclei involved in the double beta decays.

In this scenario, the ongoing experimental exploration of heavy-ion-induced DCE reactions on isotopes candidates for 0νββ-decay can provide unique information toward the determination of NMEs for 0νββ-decay. Of course, the DCE reaction process needs to be described in detail to unfold the relevant nuclear response from the measured DCE cross-sections, which is by itself an interesting research goal for nuclear reaction theory [12]. If so, DCE NMEs can be inferred by measured cross-sections under controlled laboratory conditions and can be connected to NMEs relevant for 0νββ-decay [13, 14]. The analysis of the net of direct quasi-elastic reactions occurring in the projectile–target collision can provide additional information on the nuclear response of 0νββ-decay candidate nuclei since they probe selected degrees of freedom of nuclear structure. For instance, the study of single charge exchange, within the same reaction scheme, allows one to constrain the nuclear response to proton (creation)–neutron (destruction), or neutron (creation)–proton (destruction) operators [15, 16].

DCE cross-sections can be studied within the same overall reaction coupling scheme. Different reaction mechanisms potentially contribute: (1) the multinucleon transfer, where two protons and two neutrons are transferred in opposite directions between the colliding partners; (2) the sequential exchange of two uncorrelated mesons (massive particles mediating the strong interaction), mainly two charged pions, between two protons and two neutrons of the target and the projectile [17]; (3) the exchange of correlated mesons between two protons and two neutrons of target and projectile, named the "Majorana mechanism" [12]. Among these, the Majorana mechanism is a very promising source of information about the actual nuclear response relevant for 0νββ-decay. A challenge is to disentangle such components in the measured DCE cross-sections, as they are indistinguishable and thus their amplitudes add coherently. Recent developments on both the experimental and theoretical sides indicate that, at very forward scattering angles, the DCE cross-section has a negligible contribution from multinucleon transfer and that the shape of the angular distributions for Majorana DCE is different from that originating from uncorrelated meson exchange [12]. As said before, all these studies can greatly profit from the possibility to set controllable laboratory conditions. For instance, repeating the same experiment at different beam en-

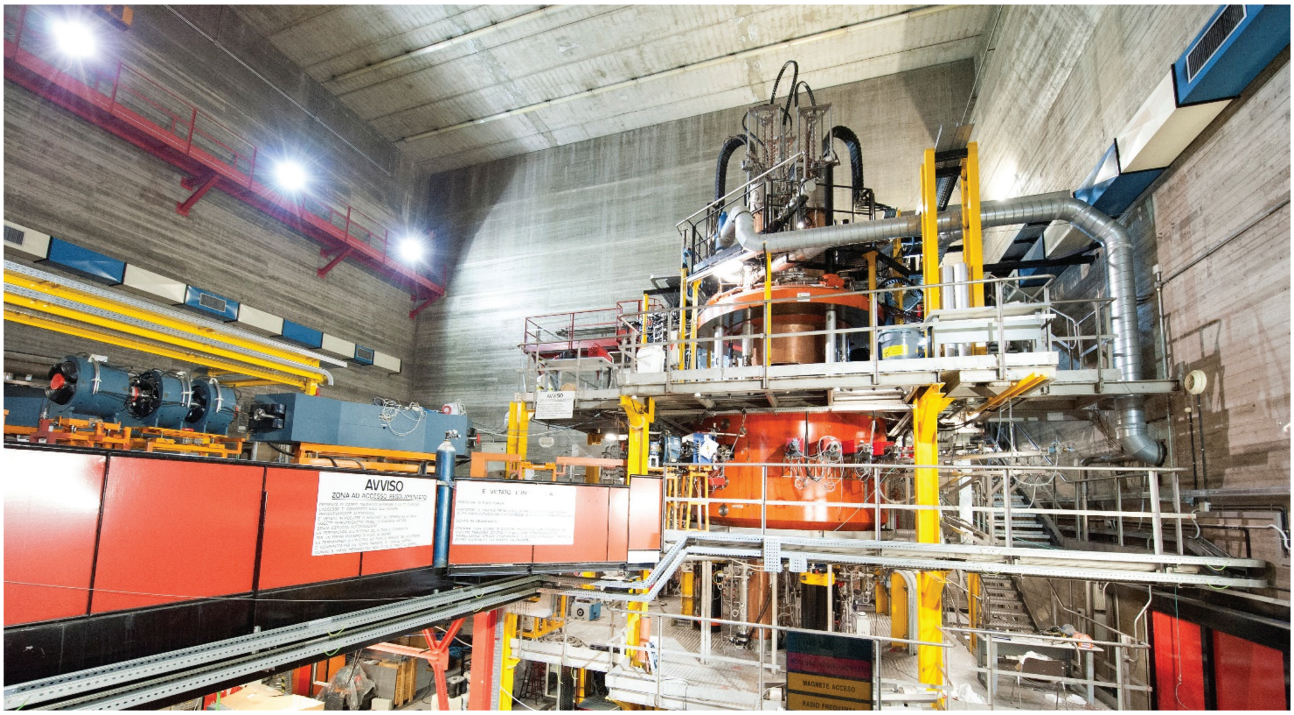

Figure 1. *The CS at the INFN-LNS laboratory.*

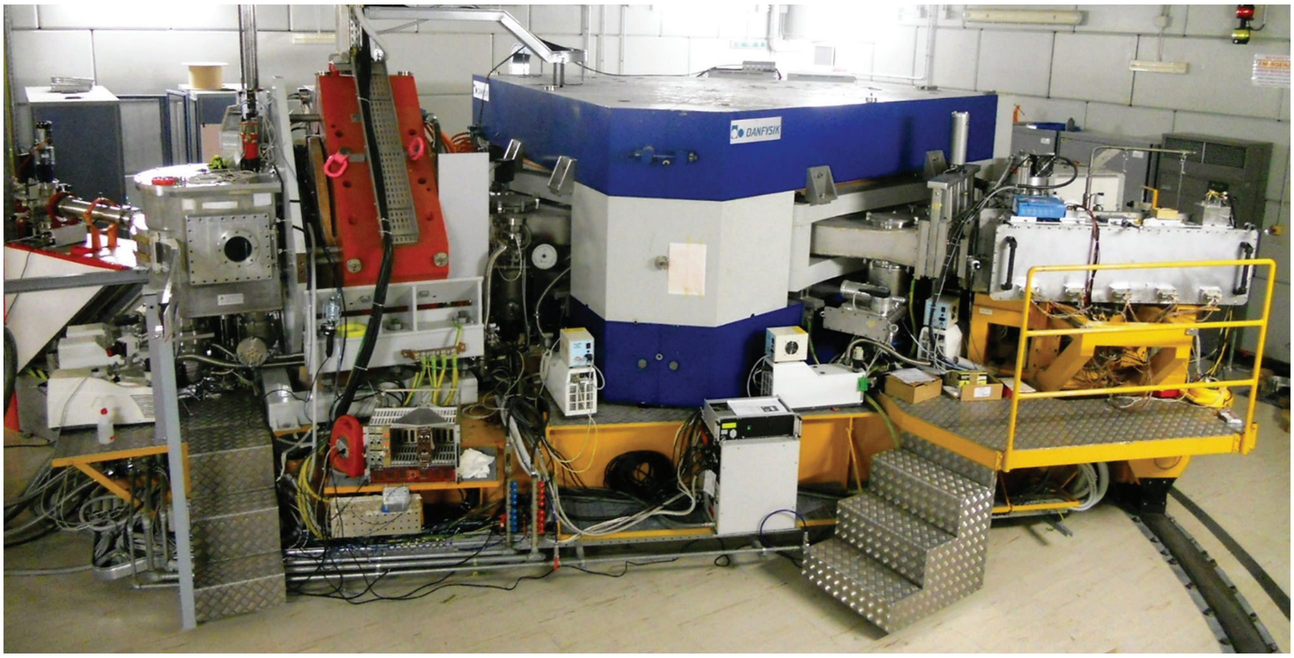

Figure 2. *The MAGNEX spectrometer at the INFN-LNS laboratory.*

ergies allows putting further constraints on all the extracted nuclear structure observables.

Nuclear structure theoretical models can thus be folded with reaction theory and be confronted with a wealth of measured observables, giving rise to a new "class" of constrained theories to be adopted for the determination of 0νββ-decay NMEs.

News from the NUMEN Project

NUMEN has started to move along this line in recent years. Since 2013, the collaboration has refined more and more its approach to heavy-ion DCE investigation, overcoming some of the experimental challenges and developing advanced approaches to data analysis. This activity has also allowed a pioneering extraction of quantitative information on NMEs from DCE reactions [13]. So far, however, these efforts have been partly hindered by the tiny cross-section for DCE reactions and the challenging selectivity required to disentangle DCE events from the large background from other, more probable, reaction channels. But since these setbacks, major upgrades are being made to the INFN-LNS facility in Catania, which are designed to make this task far easier.

The goal of NUMEN is to investigate the nuclear response to DCE reactions for all the isotopes explored by present and future studies of 0νββ-decay. Several aspects of the project require the development of innovative techniques, for both experiment setup and theoretical interpretation of the collected data.

In particular, the beam current delivered for the NUMEN experiments will be raised by more than three orders of magnitudes (from less than 10^{10} particle-per-second [pps] of the present experiments up to 10^{13} pps). From the beam side, this requires the implementation of advanced solutions for the beam production, acceleration, diagnostics, and radiation safety. From the experiment side one needs to develop suitable technologies, able to cope with the large power dissipation due to the beam–target interaction. An additional challenge is the detection of reaction products, including charged ejectiles and gamma-rays, under unprecedented fluxes of radiation from gamma-rays, neutrons, and charged particles, still preserving the high resolution and sensitivity to DCE of the present facility [18].

With the help of these facilities, along with new cutting-edge theoretical calculations that are being developed, NUMEN soon hopes to embark on the most extensive search for 0νββ NMEs ever undertaken. The INFN-LNS facility is today unique for this research in worldwide context and will likely be in view of the ongoing major upgrade of the whole research infrastructure. In summary, NUMEN is a challenging project at the intersection of nuclear and neutrino physics, driven by a stimulating physics case and opening interesting scientific scenarios and potential technological fallout.

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CPEDM: A Storage Ring Facility for Charged-Particle EDM Searches

Scientific Background: Symmetries and Physics Beyond the Standard Model

Permanent electric dipole moments (EDM) of particles violate both time reversal (T) and parity (P) invariance and, on the basis of the CPT (C represents charge conjugation) theorem, they also violate the combined symmetry CP (Charge-Parity Violation: CPV). Such a symmetry breaking is thought to be responsible for the different behavior of particles and antiparticles, leading, for example, to the apparent matter–antimatter asymmetry in the Universe. CPV is found in the electroweak part of the standard model (SM) of particle physics but—because SM-CPV is much too weak to explain the matter–antimatter asymmetry—other sources must be sought. An obvious observable to investigate is an EDM, because the SM-EDM values are unmeasurably small with current experimental techniques, finding an EDM would very probably also indicate new physics, not contained in the SM [1]. After a possible discovery of an EDM, different systems will have to be investigated in order to identify the CPV-source. Because of its exceptional science case, EDMs are searched for in various systems, hitherto, for example, for the electron bound in atoms and molecules or the free neutron, but only impressive upper limits have been obtained so far [2].

Recently, it has been proposed to use polarized charged particles, like protons, deuterons, and ^{3}He, confined in a storage ring [3]. The measurement principle is based on the time development of the polarization vector—which is parallel to the EDM—subject to a radial electric field: a beam of particles, originally polarized in the horizontal plane along the direction of the momentum vector, slowly develops a vertical component. In spite of its simplicity, this represents an enormously challenging project due to the smallness of the expected effect.

As of late, oscillating EDMs as an additional observable have come into focus [4]: axions and axion-like particles (ALPs) induce oscillating EDMs with an oscillation frequency proportional to their mass. Since these yet unobserved particles are well-motivated candidates for dark matter (DM) with largely unconstrained masses, they are also searched for with different approaches: EDM storage rings are very well suited to allow for these searches over a wide range of masses/oscillation frequencies. In order to observe axions/ALPs, the stored particle spins have to precess at the oscillation frequency of the axion field to produce a resonant build-up of the vertical polarization. In contrast to static EDM measurements where the spins have to be "frozen" parallel to the momentum vector in the horizontal plane, this principle can already be applied in storage rings with magnetic bending, such as COSY (COoler SYnchrotron at Forschungszentrum Jülich, Germany). In addition, oscillating EDM searches are considered to be less sensitive to systematic effects compared to static EDMs in a ring. A schematic overview of the EDM science case is given in Figure 1.

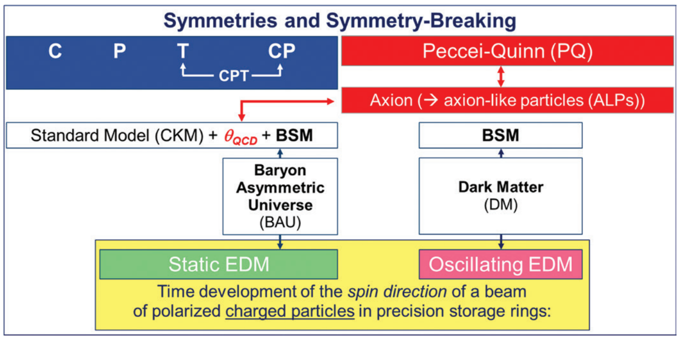

Figure 1. *Summary of the scientific background: discrete symmetries (C, P, T, and combinations thereof) and the presumed Peccei-Quinn symmetry (PQ) together with their breaking (CP- and PQ symmetry violation) may be related to static and oscillating EDMs. Static EDMs may be responsible for the baryon asymmetric universe, while oscillating EDMs could be due to the axion and/or ALPs as DM candidates. Experimentally, both can be investigated by a measurement of the time development of the spins of a beam of charged particles circulating in a storage ring.*

Experimental Method for Charged Particles: Use of Polarized Beams in Storage Rings

The measurement of an EDM always relies on its interaction with an electric field. For a charged particle, such a field accelerates the object—thus, in order to observe a possible effect due to an EDM, the particle (in practice a beam of particles) needs to be confined in a macroscopic trap, a storage ring. Since the EDM vector will always be parallel to the particlés spin vector, it suffices to observe the time development of a polarized particle beam due to the interaction with present static and motional electric fields of the storage ring. If one aligns the spins in the horizontal plane parallel to the momentum vector, a radial electric field acting on the EDM (see Figure 2) produces a torque, which tilts the spin out-of-plane: this constitutes the EDM observable.

Although a measurement in principle might be deemed very simple, the challenge (for any permanent or oscillating EDM search) lies in the fact that EDMs are very small—the neutron EDM upper limit is now at d < 1.8 x 10^{-26} e.cm (90% CL) [5]. Spurious effects, in particular those connected with the much larger magnetic moment of the particle, have to be under control at the utmost level.

Actually, the time development of the spin of a particle in electric and magnetic fields is described by the so called Thomas-BMT (Bargmann-Michel-Telegdi) equation [6]. Inspecting the various contributions of the equation, it turns out that for protons (with a positive anomalous magnetic moment) in a ring with electric bending elements, the effects of the magnetic moment disappear for a magic momentum p = 700.7 MeV/c (corresponding to a kinetic energy of 232.8 MeV). The storage ring will thus be purely electric, which allows us to simultaneously operate with counter-rotating beams—a scheme foreseen to mitigate systematic effects. For technically feasible electric fields (a few MV/m), the required precision all-electric storage ring will have a circumference of a few hundred meters [7].

Experimental Status and Way Ahead

Research and development (R&D) for key technologies, as well as precursor experiments to directly determine the deuteron EDM, are presently carried out by the Jülich Electric Dipole Moment Investigations (JEDI collaboration; http://collaborations.fz-juelich.de/ikp/jedi/) at the cooler storage ring COSY at Forschungszentrum Jülich in Germany; for achievements see the previous feature article in *Nuclear Physics News* [8]. Since COSY is a purely magnetic storage ring, the polarization vector precesses in the horizontal plane and an EDM just lead to a tiny oscillation amplitude of the vertical polarization component (Figure 2), very much like in the case of the muon g-2 experiment at Fermilab. Using a radio-frequency (RF) Wien filter, however, operating at the same frequency as the spin precession, a vertical polarization build-up due to the EDM occurs. The RF Wien filter method is described in Ref. [9]. Unfortunately many systematic effects, like, for example, misaligned magnets, lead to the same effect. In an experiment using deuterons with a momentum of 970 MeV/c such a build-up could be observed (Figure 3). At this point, the vertical polarization component is dominated by systematic effects that are under investigation using spin-tracking simulations of the storage ring. In addition, the precision that can ultimately be reached in COSY is limited to values above 10^{-22} e.cm. It is evident that a much larger precision, similar to the one reached in neutron EDM experiments or even beyond, can only be achieved with a dedicated EDM ring.

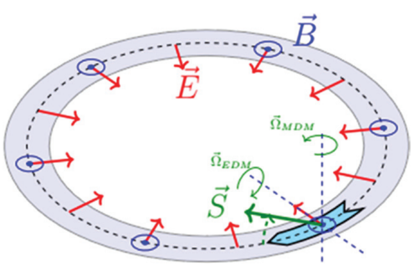

Figure 2. *Schematic drawing of fields (E, B) acting on a particle circulating in a storage ring, the particle's spin vector (S), as well as the relevant precession vectors Ω_{EDM} and Ω_{MDM}.*

On the way toward such a precision storage ring, a number of technological and metrological challenges need to be mastered (e.g., storage and spin coherence time of the beams, residual radial magnetic fields that mimic an EDM, or the required precision of beam position monitors). The conclusion of the JEDI and Charged-Particle EDM (CPEDM; http://pbc.web.cern.ch/edm/edm-default.htm) collaborations is that the accomplishment of the task requires a stepwise approach (see also Figure 4):

- **Step 1: Proof-of-capability** (ongoing activity). Perform R&D for key components and a first-ever deuteron EDM "precursor experiment" at the magnetic storage ring COSY-Jülich.
- **Step 2: Proof-of-principle** (time frame: next 5 to 10 years). Design, build, and operate a prototype ring with beam kinetic energy between 30 and 45 MeV in two steps: (1) an all-electric ring for CW/CCW operation, but not at the magic momentum, and (2) a "frozen spin" operation after complementing the ring with B-fields, to perform first a competitive proton (pEDM) experiment (with a sensitivity similar to the neutron EDM).
- **Step 3: Precision experiment** (time frame: next 10 to 15 years). Design, build, and operate a dedicated storage ring at the magic momentum (all-electric; beam kinetic energy 232.8 MeV; momentum 700.7 MeV/c) to push the pEDM sensitivity significantly below that of the neutron EDM; the final goal is 10^{-29} e cm.

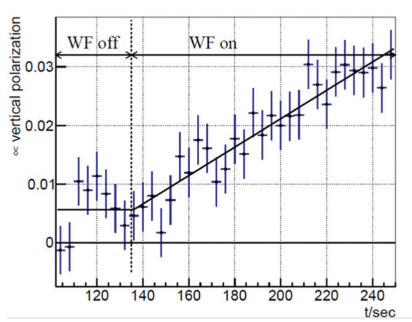

Figure 3. *Experimental result obtained for the time development of the vertical polarization of a deuteron beam in COSY. The polarization increase after the RF Wien filter (WF) is switched on is dominated by systematic effects that are currently under investigation.*

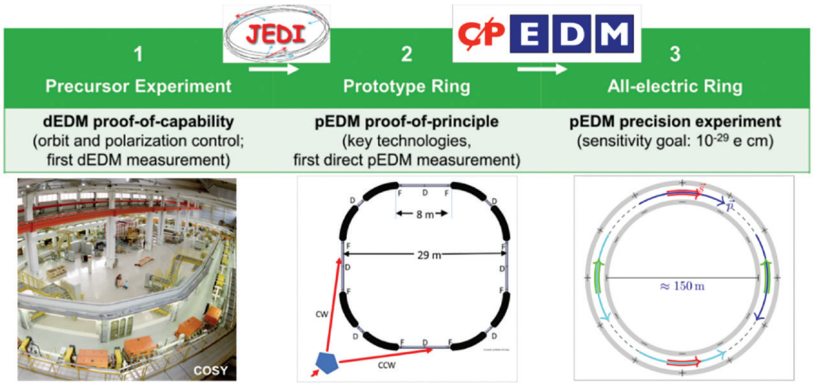

Figure 4. *Overview of the stepwise approach to a precision storage ring for charged particle EDM searches.*

The first objective is to convene and combine technological and scientific expertise in accelerator, nuclear/hadron, and particle physics for a storage-ring EDM project. The emphasis will be on Step 2 as the inevitable milestone toward Step 3:

- Prepare a Technical Design Report for the prototype ring, then build and operate it. The ring layout should be host-site independent.
- Conduct a pEDM measurement as proof-of-principle and pave the way for the design of the final high-precision ring.
- In addition: exploit the prototype ring to conduct a DM (axions/ALPs) scan by searching for oscillating EDMs.

In summary: CPEDM is a long-term project with an exciting science case that undoubtedly has the potential to become a European research flagship.

Acknowledgments

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Nuclear Applications

Advances in nuclear physics are driven by advances in detector technology. Such technology has obvious relevance to other science areas, such as space science and high-energy physics, but it also has broad application to societal challenges in sectors as diverse as homeland security, nuclear decommissioning, and medical imaging [1]. Our group has had success in entering many of these application spaces, both developing new methodologies and applying the latest in detector technology. In many cases, we have partnered with British companies such as Kromek PLC to bring new products to market. The work has been supported by direct industrial funding as well as research grants from UK funding councils such a STFC, the funding council for nuclear physics and Innovate-UK, which supports research and development (R&D) partnerships between academic researchers and industry.

Here, we discuss three applications we have developed, which, depending on the application, concern detection of all the main classes of ionizing radiation: alpha particles, beta particles, gamma rays, and (thermal) neutrons. The technologies used to address these applications vary with the application and chiefly employ semiconductor detectors (i.e., silicon) and scintillator detectors. In particular, our work has taken advantage of the advent of silicon photomultiplier (SiPM) technology to replace conventional photomultiplier tubes for scintillation light detection. SiPMs are compact and robust, and operate at low voltage (30–60 V). Their low power consumption allows them to be operated from a battery and, perhaps more importantly for industrial applications, they are inexpensive.

Flexible Alpha Particle Detectors

Our first example is in the area of nuclear decommissioning. Nuclear plants, such as the Sellafield reprocessing plant in Cumbria, UK, have thousands of kilometers of pipes, typically 2" in diameter, through which, at some time, liquid containing radioactive materials may have been flowing. The decommissioning and disposal of such pipework is complicated by the need to show, at the point of disposal, that the pipe is free of contamination to stringent limits. Some potential contaminants are essentially alpha-emitting only, such as Pu-239. Due to the short range of alpha particles in matter, it is impossible to detect such contamination from outside of the pipe; the pipe would have to be sectioned and cut open to carry out a time-consuming and expensive inspection procedure.

Working with Kromek PLC and Sellafield Sites, we developed a pipeline inspection device based on flexible silicon detectors. Our starting point was recognizing that at a thickness of around 50-um, silicon wafers become highly flexible and can be bent into a true cylindrical geometry. A cylindrical detector matches the geometry of the pipe and will have an identical efficiency all the way around. Using detector-grade silicon wafers, we fabricated our own prototype detectors using the clean room facility at the University of York Nanocentre [2]. These flexible detectors are shown in Figure 1, along with the prototype pipeline inspection device, which can be pulled down a pipe on a tether.

The thinness of the silicon sensors ensures they are insensitive to other types of radiation, such as gamma radiation, which may be present in the surrounding area. GEANT4 (https://geant4.web.cern.ch) simulations confirm that the prototype detector system can demonstrate that the level of alpha activity is below the prescribed limit of 0.4 Bq/cm^2, moving down the pipe at a rate of about 1 meter every three minutes.

Figure 1. *Alphaflex pipeline inspection guide. The flexible silicon detectors are shown on the left hand side.*

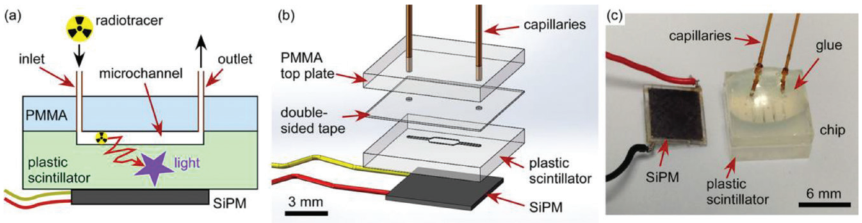

Figure 2. *Plastic scintillator sensor embedded into a microfluidic chip for PET isotope assay.*

Microfluidic Chip–Based Sensors for PET Isotope Assay

We now turn to an example in the area of medical applications. Assay of isotopes used in positron emission tomography (PET) is conventionally carried out through measurements of annihilation gamma rays using a NaI(Tl) detector. However, such a system is necessarily bulky and requires extensive shielding. There is an increasing push to move the manipulation of radiotracers in solution to microfluidic chips. This has significant advantages in terms of reducing the exposure of the isotopes in solution to surfaces that could lead to contamination. We were asked by colleagues at the University of Hull whether we could develop a system to detect the level of activity of a PET isotope sample within a microfluidic chip. We realized immediately that it was more suitable in this configuration to directly detect the positrons emitted rather than the more penetrating annihilation radiation, as such positrons have a range of only about 1 mm in plastic compared to the long range of 511-keV annihilation gamma rays in matter. The positron detection could be achieved with a plastic scintillator integrated into the microfluidic chip where the scintillation light was collected with a silicon photomultiplier (SiPM). The apparatus developed for such measurements is shown in Figure 2. Tests carried out with the prototype detector indicated that it could perform with sensitivity similar to a conventional detector system [3]. This detector technology has now been patented and further development is ongoing.

We next describe an application in the area of gamma-ray detection for homeland security.

Wearable Gamma-Ray Detectors for Homeland Security

It is often said that the first priority of government is the safety and security of its citizens. Accordingly, homeland security is an area of high importance internationally; a key area of interest is the detection and location of illicit radiological material in the environment. Such material could be used to fabricate a “dirty bomb” (i.e., a radiological weapon where a conventional explosive is used to disperse radioactive material to create panic in an urban environment). Gamma-ray detectors designed to solve these challenges need to carry out several functions (i.e., to quantify the level of radiation, determine its origin in terms of the specific radioactive isotope, and locate it spatially within the built environment. To cover a large area, many detectors (in the 100s or even 1,000s) would need to be deployed, requiring them to be not only sensitive but highly portable and inexpensive.

In 2013, we worked with Kromek PLC under a short knowledge transfer partnership to develop a hand-held gamma-ray detector called SIGMA. This device incorporates a CsI(Tl) scintillator crystal coupled to a SiPM and can run off battery power. Kromek initially marketed the SIGMA detector and then reconfigured it to form part of a rugged, wearable, network-capable device called the D3S (see Figure 3). This wearable detector has attracted significant sales and interest internationally. Indeed, in 2016, the U.S. government made an initial order for 10,000 units of the D3S, representing a $6M order.

The existence and capability of the D3S system is widely reported in the public domain, no doubt intended to act as a deterrent to those who would seek to do harm. The D3S is intended to be worn by first responders (e.g., police, fire, ambulance). The D3S can identify all common isotopes found in the environment, as well as those used in medical facilities and those generated as a by-product of nuclear energy production, as well as *special nuclear materials* (i.e., fissile materials associated with nuclear weapons production). Crucially, the wearer of the device does not need to do anything additional to their normal duties. The device operates autonomously, recording information on radioactivity in the environment and transmitting back to a base station along with Global Positioning System information. This allows a real-time radiological map of a city or port environment to be built up as workers carry out their regular business and alerts can be flagged should something unusual be identified.

Field trials of the D3S technology indicate a 100-fold improvement in localization and identification of sources relative to previous technology. The D3S therefore represents a very significant addition to the technologies deployed by various agencies in tackling the threat from dirty bombs and other radiological incidents. A program manager in the Defense Advanced Research Projects Agency’s Defense Sciences Office commented:

> We are extremely pleased with SIGMA’s achievements to date in

Figure 3. *The Kromek D3S RIID (radioisotope identifier).*

advancing radiation detection technology to fit in a portable, pocket-sized form factor at a price that's a fraction of what current advanced sensors cost. The ability to network hundreds, and soon many thousands of these smart detectors would make cities in the United States and around the world safer against a wide variety of radiological and nuclear threats. [4]

The D3S has also found application outside the original remit, particularly in nuclear decommissioning. For example, the D3S and SIGMA devices have been used on board drones to overfly Chernobyl and Fukushima [5] and show considerable promise in monitoring such sites and for future radiological incidents of this type.

In November 2020, Kromek launched the D5 RIID, which is a significant upgrade with respect to the D3S series. The D5 RIID replaces the CsI(Tl) scintillator crystal with a next-generation scintillator called CLLBc. In 2016–2017, we performed a program of lab-based tests for Kromek to evaluate CLLBc and to compare it with a number of similar scintillators to aid the selection of the scintillator material. Later, we studied the CLLBc detector performance as a function of the number and arrangement of SiPM sensors around the CLLBc crystal using GEANT4 simulation. Both studies were critical to the optimization of the D5 RIID device. The D5 RIID has a number of distinct advantages over the earlier D3S. The new integral detector has an energy resolution almost twice as good as the D3S, making it significantly more sensitive. Moreover, CLLBc is sensitive to both thermal neutrons and gamma rays, making it dual-functional in a single unit.

Conclusion

In conclusion, we have shown that the techniques and technology used in nuclear physics can be applied to a wide range of industrial and medical applications. In closing, we might want to address the question of why scientists working in a pure science area would want to get involved in applications work. There are of course many answers one could give about societal impact and showing relevance of your research. However, it is important to note that it is not ruled out that such industrially inspired R&D can feed back into pure research. The development of the flexible silicon detector is a good example: silicon detectors in a true cylindrical geometry would be of high value to various types of nuclear structure and nuclear astrophysics study, and is something we are exploring at the present time

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Transition of ANPhA from Former Chair to New Chair

The Asian Nuclear Physics Association (ANPhA) [1] is the central organization for nuclear physics in the Asia Pacific Region. ANPhA was established in 2010 and now consists of 11 membership countries and regions: Australia, China, Hong Kong, India, Japan, Kazakhstan, Korea, Mongolia, Myanmar, Taiwan, and Vietnam. The ANPhA chair is an official member of Working Group 9 (WG. 9) of the International Union of Pure and Applied Physics and an observer member of the Nuclear Physics European Collaboration Committee (NuPECC) and the Division of Nuclear Physics (DNP) of the European Physical Society. On 1 January 2020, the ANPhA chair was transferred from Prof. Kazuhiro Tanaka to Prof. Weiping Liu. This greeting is from both the former and new chairs to the worldwide nuclear physics community.

Prof. Kazuhiro Tanaka, Researcher (Prof. Emeritus), High Energy Accelerator Research Organization, KEK, the former Chair of ANPhA from January 2017 through December 2019
E-Mail: kazuhiro.tanaka@kek.jp

First of all, I thank you very much for your continuous support of ANPhA. During my ANPhA chair period, I was able to experience three important events for ANPhA:

Increase in the Number of Member Countries and Regions

For a long time, ANPhA has comprised seven countries and one region. However, at the board meeting in June 2019 at Jeju Island, Korea, two new counties and one region, Kazakhstan, Myanmar, and Hong Kong, joined ANPhA. This is the greatest honor for both ANPhA and myself.

Start of ANPhA (AAPPS-DNP) Awards for Young Scientists (AAYS)

AAYS are awarded to the best presentations for young participants at selected international meetings held in the Asia Pacific [2]. Although the award money is small at present (100 USD for the first rank winner, 70 USD for the second, and 50 USD for the third), their names are listed on the ANPhA home page. Currently, the number of AAYS awarded at conferences exceeds 19. In order to continue the AAYS, ANPhA decided to collect an annual fee from membership countries and regions proportional to the number of board members (i.e., 100 USD per one board member). It should be noted that the first award money for AAYS was provided by the Association of Asia Pacific Physics Societies (AAPPS) when ANPhA decided to play a role in the DNP of AAPPS.

Preparation of the Special Issue in Nuclear Physics News *for the 10th Anniversary of ANPhA*

It was the greatest work for me to prepare the special issue in *Nuclear Physics News* (*NPN*) titled “Ten Years of the Asian Nuclear Physics Association (ANPhA) and Major Accelerator Facilities for Nuclear Physics in the Asia Pacific Region” [3]. This is a summary of the present status of major accelerator facilities in the Asia Pacific region. Another purpose of this special issue I tried to realize was the first step for the “Long Range Plan” of our accelerator facilities. Therefore, some critical analysis of the construction of the major accelerator facilities must be made, namely (1) Too many concentrations for medium energy heavy-ion facilities? (2) No high energy heavy-ion accelerator and colliders in Asia Pacific; should they be constructed in near future? (3) We have to pay more attention to the construction of our next generation accelerators? And so on.

I was totally responsible for this special issue of *NPN* [3]. Therefore, I would like to know your questions, comments, and suggestions for this special issue in *NPN*, especially for the critical analysis part of this publication.

Thank you again for your continuous support of ANPhA and of myself.

Prof. Weiping Liu, China Institute for Atomic Energy, CIAE, New Chair of ANPhA with the Term of January 2020–December 2022.
E-Mail: wpliu08@gmail.com

As I am new, I would like to describe a few ongoing activities.

The First Web Board Meeting

In 2020, because of the COVID-19 pandemic, the annual board meeting of ANPhA was held through the Web, hosted by the University of Hong Kong, 11–12 December. Board members delivered country progress reports. The plan for the year 2021 and board meeting site in 2021 were discussed, and the country of Myanmar is agreeing to host the 2021 board meeting in December 2021.

ANPhA-Supported Conferences

Thanks to ANPhA’s academic influence and reputation, support to international conferences and symposiums is actively implemented, even in the situation of COVID-19. After agreement by the board members, ANPhA decided to supported the following meetings: International Summer School of the Center of Nuclear Science, the University of Tokyo (CNSSS20), Asia-Pacific Symposium for Lattice Field Theory (APLAT 2020), Strangeness Nuclear Physics (SNP) School 2020, 16th Nuclei in the Cosmos (NIC2021) conference, Nuclear Physics School for Young Scientists (NUSYS-2020) summer school in Beijing, and the 8th Asia-Pacific Conference on Few-Body Problems in Physics (APFB2020).

Several Awards

Thanks to the support from AAPPS, and the budgets collected from previous years, ANPhA AAYS could be given to young scientists in Asia to Young Scholars at CNSSS20, APLAT 2020, and the SNP School 2020.

In particular, I would like to note that the AAPPS C.N. Yang Award [4] was given to Dr. Nobuyuki Kobayashi of the Research Center for Nuclear Physics (RCNP), Osaka University. The C.N. Yang award in the field of nuclear physics is rare. As far as we know, this is the first C.N. Yang award given to the field of nuclear physics in the last decade. Also, Dr. Bing Guo, ANPhA secretary, received the Youxun Wu prize [5] for nuclear physics from the Chinese Physical Society.

Other Intentional Efforts

Participation in NuPECC activities as an observer happened in October, with mini workshop and board meetings by Prof. Weiping Liu. Weiping also participated in an AAPPS video council meeting and presented AAPPS–DNP activities on 1 December.

Two nuclear physics programs have started an A3 Foresight Program [6], which was organized under the agreement among the Japan Society of Promotion of Science, National Research Foundation of Korea, and National Natural Science Foundation of China. This program supports joint research conducted by researchers from Japan, China, and Korea. The three countries (A3) work as a consortium in advancing leading-edge research with an aim to establish a top-level research hub in Asia.

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Kazuhiro Tanaka
Prof. Emeritus, KEK, former chair of ANPhA

Weiping Liu
China Institute for Atomic Energy, CIAE, new chair of ANPhA

Virus Irradiation and COVID-19 Vaccine

All of our lives have been beset by the coronavirus disease 2019 (COVID-19), a contagious disease caused by Severe Acute Respiratory Syndrome coronavirus 2 (SARS-CoV-2). First reported in China in December 2019, coronavirus spread all over the world, causing over 2 millions deaths in 2020, still ongoing in 2021. The search for vaccines has been fast and effective, and millions of healthy subjects worldwide are receiving immunization, prepared with different advanced molecular technologies. Some vaccines currently in use (such as the Chinese Sinovac and Sinopharm, the Indian Bharat Biotech, and the French Valneva) are based on the well-established technique of whole-virus inactivation by toxic chemicals, usually β-propiolactone or formaldehyde. Inactivated or live-attenuated viruses are indeed used in virtually all vaccines in the market before COVID-19, and are therefore a well-tested and solid technique. In addition to chemicals, γ-rays were commonly used to inactivate a virus for vaccine manufacturing. The inactivation method affects the efficacy of the vaccine, because inactivation of the virus can severely damage the membrane epitopes, such as the spike protein for the SARS-CoV-2, eventually responsible for the humoral and cellular immune reaction. Therefore, the ideal inactivation method should destroy the viral RNA and spare the membrane. We have recently proposed that heavy ions can be the ideal tool for virus inactivation, because they can damage the SARS-CoV-2 with minimal damage to the spike proteins (Figure 1) [1]. Monte Carlo simulations using Geant4-DNA confirm the ratio of damage to spike proteins/RNA decrease of an order of magnitude using accelerated heavy ions rather than conventional γ-rays [2]. If the hypothesis will be confirmed experimentally, virus inactivation may become another important biomedical application of particle accelerators. The first experiment is slated for June 2021 at the GSI Helmholtz Center synchrotron SIS18 using 1 GeV/n ^{56}Fe-ions. The inactivated virus will be then tested for immunogenic response at the Helmholtz Institute for Infection Research in Braunschweig, Germany.

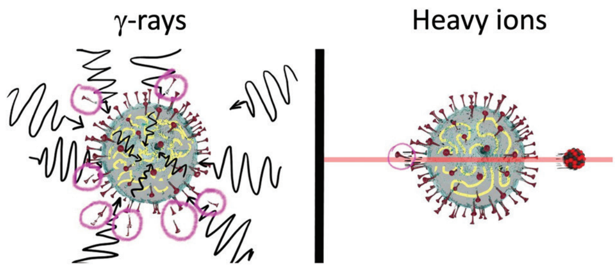

Figure 1. *Schematic representation of the action of sparsely and densely ionizing radiation on SARS-CoV-2. High doses of γ-rays can inactivate the virus, but will damage many membrane proteins, whereas a single heavy ion traversal will produce limited membrane damage while maintaining a high inactivation probability. Sparing of membrane epitopes is essential to elicit the immune response toward vaccine generation. Source: From Ref. [1], reproduced under Creative Commons CC BY-NC 3.0 license.*

References

1. M. Durante et al., *Front. Phys.* 8 (2020) 565861. doi:10.3389/fphy.2020.565861
2. Z. Francis et al., *Radiat. Res.* 195 (2020) 221–229. doi:10.1667/RADE-20-00241.1

Marco Durante
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Technische Universität Darmstadt

Support for Lebanese Scientists: Computing Facility for Multidisciplinary Research Activities

The situation in Lebanon is very bad in all respects. The economic situation is near collapse. This has been compounded by a Syrian refugee crisis, COVID-19, and by the explosion at Beirut seaport on 4 August 2020. There has been a caretaker government since 10 August 2020. In order to improve the economic and political situation in the near future, important and urgent national and international efforts are necessary.

In these difficult times, there is an initiative undertaken by the Compact Muon Solenoid (CMS) collaboration at the European Council for Nuclear Research (CERN) to support Lebanese scientists and the research efforts of Lebanese universities, four of which have joined CERN since 2016. This is through the High-Performance Computing for Lebanon (HPC4L) project. This project is endorsed by CERN through providing repurposed servers (Figure 1), which should enable computing capacity development to support all research activities, including high-energy particle physics and other interdisciplinary and multidisciplinary research activities. A CMS team will transfer knowledge/expertise-and train a dedicated support team in Lebanon that will run the HPC facility there. A fundraising activity has been started to collect funds for transport and installation of the servers, as well as on-the-job training of Lebanese experts; please see: cern.ch/fundraiser-lebanon.

Figure 1. *High-Performance Computing servers being inspected.*

Muhsin N. Harakeh
University of Groningen

In Memoriam: Akito Arima (1930–2020)

Akito Arima

Dr. Akito Arima passed away on 6 December 2020. He looked healthy and was busy until then. It has generated a very sudden and unexpected sadness: a TV station interviewed him just two days before this date. We pray for his soul from the bottom of our heart.

Dr. Arima was born in Osaka, Japan in 1930 and turned 90 years old in September 2020. Some of his ex-students were planning a special party, but the Corona epidemic forced us to postpone it, to our deep regret.

He graduated from the University of Tokyo and was granted the Doctor of Science in 1958. He joined the Argonne National Laboratory in 1959. In 1960, he returned to Tokyo and served as associate and full professors. He was engaged in research and education all over the world.

From the early days of nuclear physics, he made major contributions: five years after the birth of the "shell model" by M. G.-Mayer and J. D. Jensen, he presented, with Dr. H. Horie, the theory of configuration mixing that is a milestone of nuclear physics, serving as the backbone of today's many-body theories of nuclei. With his experiences in Argonne, he started a shell-model tradition in Japan, being still developed to date. Moreover, he initiated Japanese efforts toward supercomputing in general.

He worked on a variety of important topics in nuclear physics, ranging from the medium/meson effects on magnetic and weak processes, to α clustering and α decay, to algebraic approaches like the pseudo SU(3) scheme. I am sure that he enjoyed them all, including the famous imprisonment at the Δ-hole controversy: he was confined in a "jail" in a comic presented at a conference.

He is certainly best known for the interacting boson model, proposed with Dr. F. Iachello, on the quadrupole deformation of nuclear shapes. This model covers various shapes in a simple and unified way. Such scientific achievements brought him many honors, including Nishina Memorial awards, Japanese Academy awards, a Cultural Medal, Bonner Award, the Humboldt Award, and the Region Donour Medal. He was also instrumental in international cooperation, receiving many emeritus professorships and degrees.

He made highly respected efforts for improving the conditions of education and research in Japan, as the president of the University of Tokyo and the president of RIKEN. Indeed, he became a very important political figure: a member of the House of Councilors and the minister of education. We still recall the successful "University Poverty Story" campaign for raising government spending. In addition, he was a great poet: he brought a new style to haiku, and received the Dakotsu Prize, the highest honor for a haiku poet.

We are so grateful to Dr. Arima for his great contributions to physics and to politics for research and education. I wonder whether any scientist after him will be able to speak in person to our prime ministers on these issues as he did. We pray once again that his soul may rest in peace, after long, hard times.

Takaharu Otsuka
University of Tokyo

In Memoriam: Marc Lefort (1923–2021)

Marc Lefort

It was with great sadness that we learned of the death of Professor Marc Lefort on 16 January 2001 at the age of 98. He was the initiator of the development of heavy ion physics in France and a leading figure of this physics worldwide. He was in charge of the construction of the A Large Ion Collider Experiment (ALICE) accelerator in Orsay and then of the Grand Accélérateur National d'Ions Lourds (GANIL) in Caen, of which he was the first director.

It was in 1940 that Marc Lefort began his graduate studies at Clermont-Ferrand, studies largely troubled by the war and his activities in the resistance, a period of his life that had profoundly marked him. He did not return to the university until 1945.

At that time, under the impulse of Frédéric Joliot-Curie, the Centre National de la Recherche Scientifique (CNRS) was in full development. Marc Lefort was recruited there in 1946 by Irène Joliot-Curie, director of the "Institut du Radium" (Curie laboratory). He defended his doctorate in science in 1950, which dealt with the radiation effects on aqueous solutions.

In 1956, he joined the newly created Institute of Nuclear Physics at Orsay and there promoted the development of nuclear chemistry in France, in connection with the American School of Nuclear Chemistry, with which he made fruitful contacts.

The Institute of Nuclear Physics has thus made a major contribution to combining nuclear chemistry and nuclear physics, in particular at the level of experimental methods. Its international reach has enabled it to attract many American, Canadian, Belgian, Israeli, and Russian researchers to the Orsay site.

Marc Lefort initiated heavy ion physics worldwide by positioning France as the leader of this discipline in the 1970s. He was at the origin of the world's first "*very*" heavy ion accelerator, ALICE in Orsay. It was during this period that he was an essential player in the search for super-heavy nuclei and that his group identified new reaction channels that dominated the nucleus–nucleus collisions. The evolution at higher energy of the behavior of nuclear matter has been one of the first objectives of GANIL. Marc Lefort led the construction of this national facility, which today remains one of the major centers of heavy ion physics worldwide.

Marc Lefort is the author of many books, including one that is a reference in nuclear chemistry.

He was a brilliant teacher. Professor of Chemistry at the University of Paris and Orsay from 1963 to 1985, he knew how to create a highly attractive Ph.D. teaching in nuclear chemistry. The many students he trained remember his communicative enthusiasm, his rigor, and his great qualities as a humanist. He thus marked a whole generation that he knew how to lead in this adventure. Many of these students played an essential role in the development and operation of GANIL and thus continued its work.

Marc Lefort, "Chevalier de l'Ordre de la Légion d'Honneur," received the F. Robin Award, the highest distinction of the French Physical Society.

We are going to miss him deeply.

René Bimbot
CNRS Orsay
Daniel Guerreau
CNRS Caen
Joe Natowitz
Texas A&M University
Bernard Tamain
ENSICAEN, Caen

In Memoriam: Rolf H. Siemssen (1933–2021)

Rolf H. Siemssen

On 29 January 2021, Professor Rolf H. Siemssen passed away. He meant a lot to many of us and for the nuclear physics community nationally and internationally. We have lost a very considerate mentor and colleague and a very dear friend, who was during all his career very attentive to the scientific development of his students and the careers of his younger staff. In the following life resume, we recount his career and achievements.

Rolf was born on 15 March 1933 in Fuzhou, China. After the Second World War, he moved to Germany in 1947, together with his family. He had fond memories of the period he spent in Shanghai as a child and a young teenager. In 1953, he started his university physics studies at Tübingen and continued at Ludwig-Maximilians Universität (LMU), Munich. He obtained his Diplom in physics from Hamburg in 1958. Thereafter, he became a scientific assistant at the University of Hamburg, where he received his doctor degree in 1963 under Professor Willibald Jentschke on studies of reaction mechanisms of $\ell_p = 1$ stripping reactions. He obtained a postdoc position at Argonne National Laboratory (ANL) from 1963 to 1966. From 1966 to 1968, he took an assistant professor position at Yale University. Between 1968 and 1972, he became associate physicist at ANL. He had a very productive decade in research during his sojourn in the United States, in particular at ANL, which influenced strongly his attitude toward scientific research and collaborations. He led a number of experiments and got wide international recognition for his experiments and insights. In recognition of his scientific standing, he was appointed a professor of experimental nuclear physics at the University of Groningen in 1972 and simultaneously director of the Nuclear Physics Accelerator Institute (KVI), succeeding Professor Henk Brinkman, founder of KVI. In that year, the University of Groningen made an agreement with Stichting FOM, "Foundation for Fundamental Research of Matter," to share funding and management of KVI. KVI availed at the time a Philips Azimuthal Varying Field (AVF)-cyclotron.

Upon taking over as director, Rolf embarked on increasing the scientific and technical staff and started a visitor program to ensure that KVI becomes a successful research institute with high scientific potential and international visibility. Rolf realized the importance of having a strong theory group at KVI for stimulating the experimental nuclear physics research. He strengthened the group by hiring new members and inviting internationally well-known theorists for long stays at KVI. In 1974, Rolf attracted Francesco Iachello to KVI and invited Akito Arima to visit KVI for a three-month period. This was a master move, as during that period Arima and Iachello laid the foundation of the interacting boson model.

In the beginning of the 1980s, a project for axial injection to the cyclotron was realized, allowing injection of heavy ions from an external source. This started the heavy-ion research program, whose potential increased tremendously by the installation of the Electron Cyclotron Resonance Ion Source (ECRIS) source in 1982, allowing a larger variety of heavy ions at higher energies. This also gave the opportunity to start an atomic physics program, prompting the Atomic Physics Group of the faculty to move to KVI.

In the early 1980s, after many discussions in the Dutch nuclear physics community, a decision was finally made in 1985 to build a new superconducting cyclotron (AGOR) at Institut de Physique Nucléaire (IPN) Orsay in a joint Dutch–French effort. From 1986 to 1991, Rolf, as KVI director and FOM liaison, was cochair of the AGOR Management Board, together with P. Lehman, director of IN2P3/CNRS . He played a decisive role in the success of this unique scientific venture. On 1 January 1991, Rolf retired as director of KVI before AGOR was finished and moved to KVI. Fortunately, AGOR delivered its first beams in May 1994 at Orsay and then was moved and installed at KVI, delivering its first beams in 1996 before his final retirement as professor in 1998.

Rolf was an American Physical Society fellow since 1972, a member of the Royal Netherlands Academy of Arts and Sciences since 1987, and became a foreign member of the Polish Academy of Arts and Sciences in 2006. He received the title Officer in the Order of Oranje Nassau.

Rolf served the international nuclear physics community by taking part in evaluation and advisory committees worldwide. He was also a long time editor of *Physics Letters* B.

Ad van den Berg
University of Groningen, Netherlands
Sydney Gales
IJCLab, Orsay, France
Muhsin Harakeh
University of Groningen, Netherlands

2021

September 5–10
Lisbon, Portugal. 22nd Particles & Nuclei International Conference - PANIC 2020
http://www.lip.pt/panic2020

September 5–10
Brasov, Romania. International Conference on HYPERFINE Interactions and their Applications
https://infim.ro/hyperfine-2021/

September 8-10
East Lansing, MI, USA. 15th workshop on Shielding aspects of Accelerators, Targets, and Irradiation Facilities (SATIF-15)
https://indico.frib.msu.edu/event/19/

September 12–17
Prague, Czech Republic. Applied Nuclear Physics Conference 2020
https://www.anpc2020.cz/September 21–25

September 12–17
Vienna, Austria. EXA 2021
https://indico.gsi.de/event/9289/

September 13–16
Pohang, Korea. 10th International Beam Instrumentation Conference IBIC 2021
https://www.indico.kr/event/22/

September 13–17
Cape Town, South Africa. Advance Nuclear Science and Technology Techniques (ANSTT3) Workshop
https://indico.tlabs.ac.za/event/92/

September 20–23
East Lansing, MI, USA. 15th workshop on Shielding aspects of Accelerators, Targets, and Irradiation Facilities (SATIF-15)
https://indico.frib.msu.edu/event/19/

September 20–24
Hoedspruit region, South Africa. African Nuclear Physics Conference (ANPC 2021)
https://indico.tlabs.ac.za/event/101/

September 21–25
Chengdu, China. NIC2020
http://www.juna.ac.cn/nic2020

October 4–8
Athens, Greece. 7th International Workshop on Compound-Nuclear Reactions and Related Topics CNR*20
http://www.inp.demokritos.gr/cnr2020/

October 11–15
Catania, Italy. NuSym 2021
https://agenda.infn.it/event/21920/

October 12–16
Naples, Italy. Advances and Challenges in Nuclear Fission and Quasi-Fission for the SuperHeavy Elements
https://agenda.infn.it/event/20777/

October 18–22
Shanghai, China. ICALEPCS 2021
https://indico.ssrf.ac.cn/event/1/

October 31–November 6
Sanibel Island, FL, USA. 7th International Conference on "Fission and Properties of Neutron-Rich Nuclei" (ICFN7)
https://indico.frib.msu.edu/event/10/

November 14–21
Shizuoka, Japan. 8th International Conference on Heavy-Ion Collisions at Near-barrier Energies (FUSION20)
https://asrc.jaea.go.jp/soshiki/gr/HENS-gr/fusion20/index.html

2022

March 14–17
Sao Paulo, Brazil. 7th IEA International workshop: Clustering aspects in nuclei and reactions
https://sites.google.com/view/7thcluster/home

May 2–6
Guelph, Canada. Workshop on Shape Coexistence, E0 Transitions, and Related Topics
https://www.physics.uoguelph.ca/shape-coexistence-workshop-may-2-6-2022

May 3–6
Madrid, Spain. 2nd Joint ECFA-NuPECC-APPEC Seminar JENAS
http://www.nupecc.org/jenaa/?display=seminars

June 12–17
Varenna, Italy. 16th Varenna Conference on Nuclear Reaction Mechanisms (NRM2022)
https://indico.cern.ch/event/894489/

June 12–17
Catania, Italy. 7th International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7)
https://agenda.infn.it/event/21964/

June 12–17
Budapest, Hungary. Astrophysics with Radioactive Isotopes (AwRI2020)
https://indico.cern.ch/event/820113/

June 27–July 1
Santiago de Compostela, Spain. DREB (Direct Reaction with Exotic Beams)
https://indico.cern.ch/event/812362/

July 3–9
Rila, Bulgaria. 39th International Workshop on Nuclear Theory IWNT39
http://ntl.inrne.bas.bg/workshop/2021/

August 1–6
Stavanger, Norway. XIVth Quark Confinement and the Hadron Spectrum
http://www.ux.uis.no/confxiv/

August 2–September 2
Liverpool, UK. 30th Linear Accelerator Conference (LINAC)
http://linac2022.org/

August 22–26
Vienna, Austria. Second International Conference on Applications of Radiation Science and Technology (ICARST-2021)
https://www.iaea.org/events/icarst-2021

August 28¬–September 4
Zakopane, Poland. 55th Zakopane Conference on Nuclear Physics
https://zakopane2020.ifj.edu.pl/

September 5–9
Bonn, Germany. 9th International Conference on Quarks and Nuclear Physics QNP2022
https://www.jlab.org/indico/event/344/

2023

June 4–9
Avignon, France. ARIS 2020
http://aris2020.eu

Due to the current situation with Covid-19, please check the up-to-date situation under http://www.nupecc.org/index.php?display=events or go to the conference website directly.