Appendix to IUPAP Report 41

September 2019

Following up on the IUPAP WG.9 Nuclear Science Symposium from August 29-30,2017, at the RIKEN Tokyo Office, giving an overview of the status of Nuclear Science, it was decided for the 2019 Nuclear Science Symposium at the University of Notre Dame London Global Gateway, August 3-4, to highlight a series of nine topics of great current interest (after some discussions with the Office of Nuclear Science in the US Department of Energy).

Here are presented the written versions of the nine topics chosen:

1) "The Physics with an Electron-Ion Collider from a Worldwide Perspective" - Richard G. Milner [MIT]

2) "Quantum Information Science and Nuclear Physics" - Martin Savage [University of Washington]

3) "The Multi-messenger Signals from Gravitational Waves and the Implications for Nucleosynthesis" - Ian Harry [University of Portsmouth]

4) "ISOL-based and Fragmentation-based Production of Rare Isotope Beams" - Maria Jose Garcia Borge [CERN]

5) "Hunting for Dark Matter with Nuclei and Neutron Stars" - Sanjay K. Reddy [INT/University of Washington]

6) "The Structure of the Nucleon" - Marc Vanderhaeghen [Mainz Universitaet]

7) "Neutrinos and Nuclear Physics" - Joshua Klein [University of Pennsylvania]

8) "EDM Searches, a Worldwide Perspective" - Guillaume Pignol [LPSC, Universite de Grenoble]

9) "Searching for New Physics: the Fundamental Symmetry Experiments" - Vincenzo Cirigliano [LANL]

It is the intention to publish these nine synopses together in the scientific literature.

Willem T.H. van Oers
TRIUMF
September 30, 2019

The Physics with an Electron-Ion Collider from a Worldwide Perspective

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Abstract. The science case for a U.S.-based Electron-Ion Collider (EIC) has been developed by the QCD community over two decades. Most recently, it is summarized in the 2015 White Paper *Electron-Ion Collider: The Next QCD Frontier* and has been favorably reviewed in 2018 by a committee appointed by the U.S. National Academy of Sciences. The author presents a personal perspective based on these two reports.

1. Introduction

Fundamental, curiosity-driven science is funded by developed societies in large part because it is one of the best investments in the future. For example, the study of the fundamental structure of matter over about two centuries underpins modern human civilization. There is a continual cycle of discovery, understanding and application leading to further discovery. The timescales can be long. For example, Maxwell's equations developed in the mid-nineteenth century to describe simple electrical and magnetic laboratory experiments of that time are the basis for twenty-first century communications. Fundamental experiments by nuclear physicists in the mid-twentieth century to understand spin gave rise to the common medical diagnostic tool, magnetic resonance imaging (MRI). Quantum mechanics, developed about a century ago to describe atomic systems, now is viewed as having great potential for realizing more effective twenty-first century computers.

The Standard Model (SM), shown schematically in Fig. 1, represents an enormous intellectual human achievement. At least eighteen Noble prizes in Physics have been awarded since 1950 to the physicists who made the key experimental discoveries and critical theoretical insights. However, the SM is framed in terms of particles, most of which are undetectable in the laboratory or are very short-lived. The electron and photon stand apart in Fig. 1 as being stable and straightforwardly accessible in the laboratory, and, consequently and not surprisingly, the quantum theory of electrons

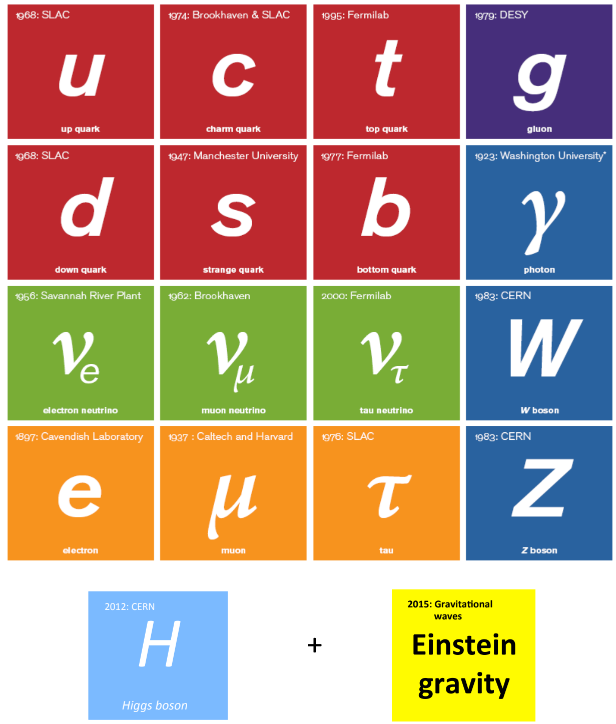

Figure 1. Schematic illustration of the fundamental structure of the Standard Model showing the fermions (quarks and leptons), exchange bosons, Higgs boson and Einstein gravity.

and photons, Quantum Electrodynamics (QED,) is the best understood aspect of the SM.

The study of the fundamental structure of matter has long relied on electron-proton scattering to determine the pointlike quark constituents of the nucleons, the momentum distribution of nucleons in the nucleus, and the most precise information on systems bound by the strong (or nuclear) force [1]. Thus, the discovery of quarks provided a cornerstone of the theory of the strong force, Quantum Chromodynamics (QCD). QCD describes the the proton, the nucleus of the hydrogen atom, as a highly relativistic system of quarks and gluons interacting via a color force. Basic properties of the proton, like its mass (explains most of what is measured when you stand on the bathroom scales) and spin (the property manipulated in an MRI scan) arise in QCD from these complicated interactions in ways we do not yet understand.

Nuclear physicists have developed a powerful theory of nuclei as a system of protons and neutrons using a parametrization of the interaction between these constituents that are readily detectable in the laboratory. This theory is used to understand the energy processes in the universe as well as important societal applications like nuclear energy and medicine. If quarks and gluons are the fundamental particles, can the theory of nuclei be derived from QCD? Can the origin of the mass and spin of the proton be understood in terms of the quarks and gluons of QCD? Can quarks and gluons exhibit different behavior when bound in the nucleus rather than the proton?

2. Why a U.S.-based EIC now?

The U.S. QCD community over about two decades has carefully considered the next generation accelerator facility to study the fundamental structure of matter and has developed a compelling scientific case for a high-luminosity, polarized electron-ion collider (EIC). Most recently, it is summarized in the 2015 White Paper *Electron-Ion Collider: The Next QCD Frontier* [2] and has been favorably reviewed in 2018 by a committee appointed by the U.S. National Academy of Sciences (NAS) [3].

The collision at high energy of an electron and proton probes directly the quark substructure when interpreted in a boosted reference frame [4]. In this boosted frame, snaphots of the quarks can be taken with different spatial resolutions ($1/Q$) and shutter exposure times (x). Both Q^2 and x are defined independently of the reference frame and can be precisely varied experimentally to probe different aspects of the proton substructure. Fig. 2 shows schematically (in analogy to a camera) that at low x very rapid fluctuations of the proton's substructure can be recorded while at high x the time-average is dominant. The Q^2 dependence allows determination of the gluon distributions using the equations of QCD.

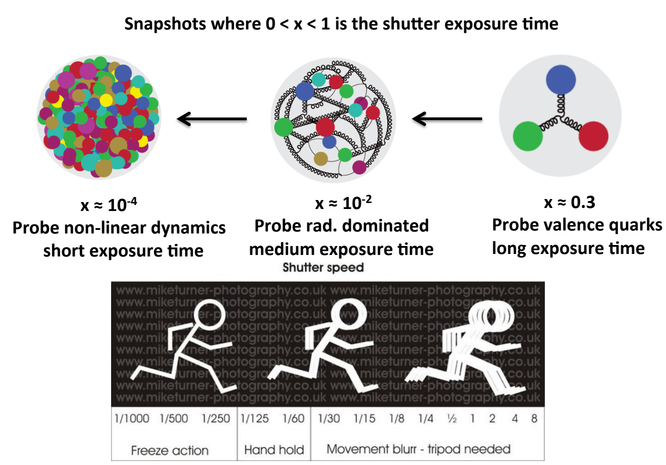

Figure 2. Visualizing proton structure: the analogy of x as the shutter exposure time.

The collider accelerator offers important advantages: it allows access to a large range of Q^2 and x; the final-state particles are distributed over a larger angular range which makes their detection much easier than for a fixed-target experiment at high energy; beams of ions from the proton to uranium can be accelerated so that QCD can be studied across the full range of available nuclei; and beams of polarized electrons, protons and light ions can be used so that the spin-dependence of fundamental process can be measured. Attaining a high-luminosity collision rate is essential for precision measurements.

An important and new aspect of high-energy QCD studies is the realization that transverse imaging of the quarks and gluons is possible. Essentially all experiments in the half-century since quarks were discovered have been of the *longitudinal* (i.e. along the incident beam direction) distributions. Nuclear physicists have figured out that by measuring processes where the incident electron loses a large fraction of of its energy to a specific final-state particle and the target stays intact, the distributions in position and momentum *transverse* to the beam can be measured. This new approach, known as *parton tomography*, is being pursued in a systematic way at long exposure time ($0.1 < x < 1$) at Jefferson Laboratory after their recent energy upgrade. A variant of tomography would study transverse motion rather than transverse position. Tomography will be pursued at EIC over a much larger range of spatial resolutions and shutter exposure times. Scanning through these pictures, starting from the valence quark regime, will enable the determination of where and how gluons and sea quarks appear and whether the gluon distribution has a compact core, smaller than the electric charge radius of the proton, or whether the gluon distribution is extended.

The EIC is a challenging accelerator to build, requiring well beyond state-of-the-art in electron and ion beam capabilities. However, the U.S. nuclear physics community uniquely possesses the required accelerator physics expertise at Brookhaven National Laboratory (BNL) and Thomas Jefferson National Accelerator Facility (TJNAF). Further, the scientific programs at the existing Relativistic Heavy Ion Collider at BNL and Continuous Electron Beam Facility at TJNAF are expected to be largely completed in about a decade. Thus, the EIC represents a clear opportunity for U.S. science both to maintain leadership at the QCD frontier as well as to regain leadership in collider accelerator technology.

3. Scientific Opportunities with EIC

An EIC is needed to address the picture of nucleons and nuclei as complex interacting many-body systems, and in particular to address three immediate and profound questions about neutrons and protons and how they are assembled to form the nuclei of atoms:

- *How does the mass of the nucleon arise? i.e.*, how do the constituents of the nucleon, the quarks, the virtual quark-antiquark pairs, and the gluons, and importantly their interactions, lead to a mass some 100 times larger than the sum of the three constituent quarks alone? Physicists are used to the mass of a bound system − a nucleus made of neutrons and protons, an atom made of a nucleus and electrons or even two black holes bound together by gravity − having a mass less than the sum of its parts. The difference is the binding energy of the system. In a nucleon, the opposite is true: half of the mass exists in the gluons that hold it together. How do gluons provide this mass?
- *How does the spin of the nucleon arise?* Spin, or internal angular momentum, is one of the basic properties of a neutron or proton, central both to understanding

atoms and their practical applications. While nucleons are made of three quarks, each with spin-$\frac{1}{2}$, the spins of these quarks constitute only a small fraction of the nucleon's spin, the rest seemingly carried by the gluon spins, the sea quarks, and the orbital motion of the quarks and gluons.

- *What are the emergent properties of dense systems of gluons?* The color force mediated by gluons is fundamentally different from the electromagnetic force that binds atoms and molecules. In particular, the force between quarks strengthens as the objects get farther apart, and quarks are permanently confined in neutrons and protons. Two questions concerning the gluons arise when nucleons are combined into nuclei: How is the gluon field modified in a nucleus to accommodate the binding of nucleons? And does a novel regime of nuclear physics emerge in the high-energy limit, a regime in which the complicated structure of the nucleus is radically simplified, leading to a state in which the whole nucleus becomes a dense gluon system?

3.1. Mass of the Proton

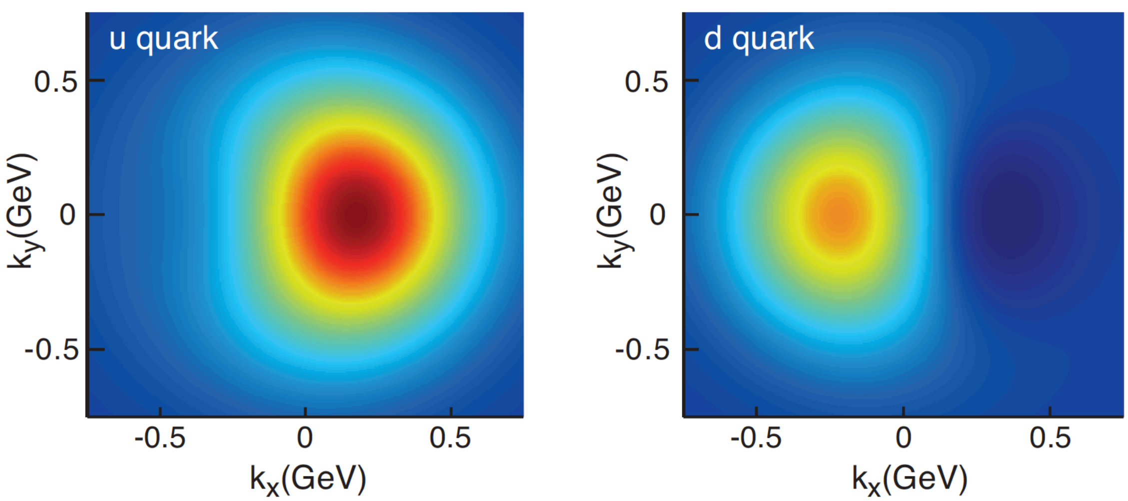

Figure 3. The density in the transverse-momentum plane for unpolarized quarks with $x = 0.1$ in a nucleon polarized along the y-direction [2].

QCD informs us that most of the mass of a nucleon is accounted for by the gluons, the virtual quark-antiquark pairs, and the kinetic energy of the quarks within it, but the details are poorly understood. There is evidence that the largest fraction of the mass is contributed by gluons, but the gluon is not electrically charged, and the energy stored in the gluon field is a form of invisible energy. The role of the gluon field energy has been inferred indirectly, but never directly measured. An EIC will address this gap in the understanding of fundamental aspects of the nucleon in several ways. First, an EIC will map the gluon distribution in the proton, both in space and in momentum, with unprecedented precision, using the new technique of parton tomography. These images can be used to analyze the coupling between spin and orbital angular momentum. An EIC would not only determine the distribution of gluons but also measure the distribution of gluonic energy density and pressure in the proton. These measurements would directly inform our understanding of the origin of mass and constrain models of the gluon field inside the nucleon. Two key features of an EIC enable measurements of gluons. The first is large kinematic coverage, which provides multiple independent avenues for accessing gluons. The second is large luminosity, which is important for identifying specific final states in high energy electron scattering. It is this information that can be used to obtain tomographic images.

3.2. Spin of the Proton

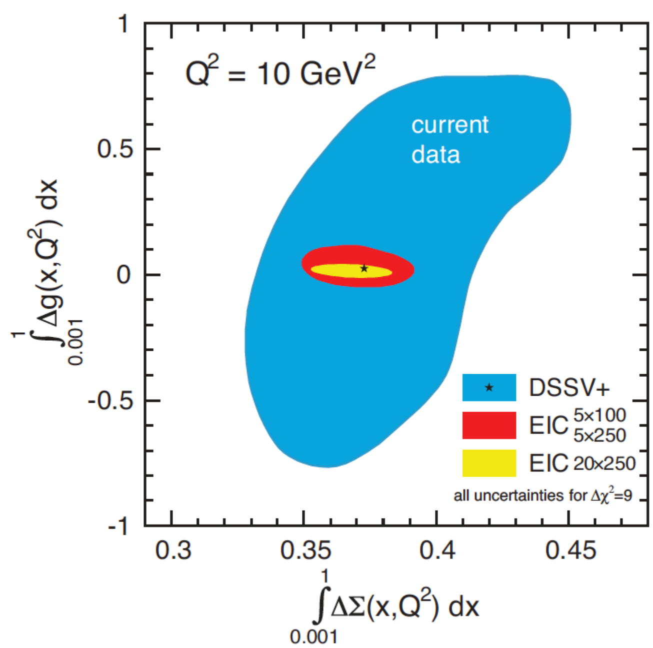

Figure 4. Present (outer area) and EIC projected (inner area) accuracies for the contributions of quarks and gluons to the spin of the proton [2].

The spin of a nucleon is an important property; through the electric charges of quarks, spin allows protons and neutrons to behave as tiny magnets. The magnetic axis is aligned with the spin axis, and external radio frequency fields can drive resonant spin transitions. This is the basis of MRI imaging and many other applications. It is remarkable that scientists do not know in detail the origin of the proton (or neutron) spin. The proton has spin $\frac{1}{2}$, and in a simple quark picture the total spin arises from three valence quarks of spin $\frac{1}{2}$ that combine to form a total spin $\frac{1}{2}$. While this naive picture qualitatively describes the observed magnetic moment of the proton, it fails quantitatively. In particular, experiments at SLAC, the European Organization for Nuclear Research (CERN), and HERA have shown that the sum of all quark spins in the nucleon accounts for only about one-third of the total spin of the proton. The remainder of the proton spin must reside in orbital angular momentum or gluon spin. An EIC can comprehensively explore these contributions. The orbital angular momentum of quarks and gluons can be extracted using the transverse position information contained in the tomographic measurements. Measurements of the gluon-spin contribution to the spin of the proton are based on the idea that the gluon can transfer its polarization to a quark-antiquark pair, which can be probed using polarized electrons.

3.3. Emergent Properties of Dense Systems of Gluons

Nuclear physics exhibits one remarkable limit where simplicity emerges. Despite the extraordinary complexity of QCD – the strength and presence of interactions among all quarks and gluons – at ordinary densities and low temperature, nuclei can be accurately modeled as collections of colorless composite particles – nucleons – interacting through long-range forces understood as arising from the exchange of mesons. An EIC would seek to explore a second regime where great simplicity may emerge, despite the inherent complexity of QCD: In this regime, quarks are predicted to behave as a nearly static source of a gluon field that reaches a limiting density, producing *dense gluonic matter*. At an EIC, this regime would manifest itself in terms of reactions on nuclei that cannot be understood in terms of approximately independent nucleons. Because the color force is so profoundly different from the electromagnetic force, there are also big differences and deep mysteries to be understood, including how quark distributions are modified in nuclei, how the gluons are distributed, and how gluons bind nucleons into nuclei. Physicists understand well why atoms retain their individual identities in molecules, but not why nucleons retain their identities within nuclei. In fact, nuclear matter can have simpler states where nucleons do not retain their individual identities, as in the quark matter seen in ultrarelativistic heavy ion collisions, and inferred in massive neutron stars. In addition, nucleons and nuclei differ from atoms and molecules because they contain so many gluons, whose implications are still not well understood. This abundance of gluons provides the opportunity to address fundamental questions about nucleons and nuclei. The number of gluons grows significantly in the small x, high-energy limit. This means that gluons must overlap in the plane transverse to the electron-ion collision. The most interesting case is when this limit can be achieved at high resolution (high Q^2), so that the number of gluons that can be packed into the transverse area of a proton or nucleus is large. An EIC of sufficiently large energy would be able to reach this limit. Under such conditions, a quantum state of *cold dense gluonic matter* may exist. Such a state is possibly analogous to Bose-Einstein condensates of clouds of cold atoms created in atomic physics laboratories. An EIC would be able to reach unprecedented gluon densities by using the concentrated gluon fields of large nuclei. Relativistic length contraction [4] implies that the number of gluons per transverse area is proportional to the radius of the nucleus, which is itself proportional to the one-third power of the nuclear mass number A. Although an EIC would operate at lower energies than HERA (which collided beams of electrons and protons), an EIC would achieve higher gluon densities because it can accelerate ions with high atomic weight.

4. EIC Accelerator Concepts

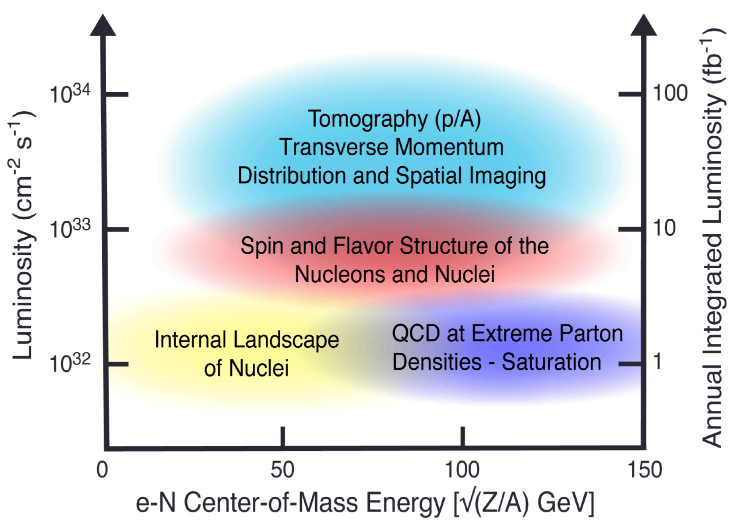

Figure 5. Collider luminosity vs. center-of-mass energy with the different scientific areas highlighted [3].

Fig. 5 shows how the scientific areas map onto the required collider luminosity and center-of-mass energy. Building an EIC capable of fully exploring the physics described in section 3 above is by no means an easy task. The machine must collide electrons with protons and other atomic nuclei (ions) over a range of energies. There must be enough collisions for the experiment to gather adequate data to elucidate or settle the known physics questions, and other questions that may emerge, in a reasonable time. A collider's ability to squeeze many particles of two beams into a tiny volume where they collide defines its luminosity. The luminosity ultimately required of an EIC is comparable to those of the highest performing colliders built to date, such as the Large Hadron Collider (LHC) at CERN and the B-meson factories at SLAC and KEK. Furthermore, given the crucial role of spin, both beams must be polarized. To achieve these goals, a host of techniques in accelerator physics and technology must be brought to bear. Only a few are mentioned here. State-of-the-art superconducting radio frequency (SRF) cavities will accelerate high-intensity beams efficiently. Further specialized radio frequency (RF) cavities will rotate the beams as they collide to optimize their overlap. Elaborate interaction region designs must squeeze two very different beams simultaneously into the tiny collision volume using advanced superconducting magnet designs. The hadron beams must be compressed in volume by sophisticated new *beam cooling* techniques that involve subtle interaction with yet other electron beams. Polarized beams require polarized particle sources, special magnets, and a further level of mastery of beam physics to preserve the polarization through the acceleration process to the collisions. Polarized colliding stored beams have been achieved before only at HERA (polarized e^+/e^- on unpolarized protons) and at RHIC (both proton beams polarized). The required specifications of the EIC accelerator are summarized as follows:

- Highly polarized (70%) electron and nucleon beams
- Ion beams from deuterons to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from $\sim$20 $-$ $\sim$100 GeV, upgradable to $\sim$140 GeV
- High collision luminosity $\sim 10^{33} - 10^{34}$ cm^{-2}s^{-1}
- Possibility to have more than one interaction region

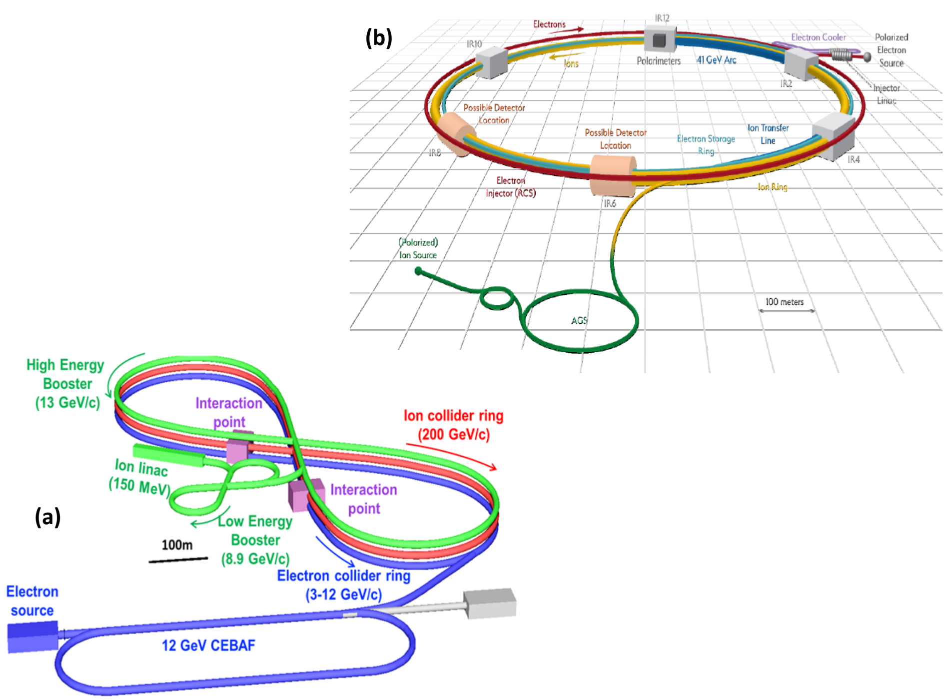

Figure 6. Schematic layouts of (a) the JLEIC conceptual accelerator design at Jefferson Laboratory and (b) the eRHIC conceptual accelerator design at Brookhaven National Laboratory.

Two conceptual EIC designs, both ring-ring configurations, have been developed: JLEIC using the existing CEBAF electron accelerator at TJNAF as an injector and eRHIC using the existing RHIC ion accelerator at BNL. Fig. 6 shows a schematic layout of both accelerator conceptual designs.

5. EIC Users Group

In 2016, the worldwide community of interested physicists organized into an EIC Users Group (EICUG). At present, this organization consists of 945 members from 190 institutions from 30 countries across the globe. The EICUG has an annual meeting that took place most recently in Paris, France in July 2019. A major conceptual study of the physics and detector concepts by EICUG members is expected to get under way by early 2020.

6. Path Forward

The U.S. Department of Energy Office of Science is working on the official launch of the EIC project as well as review of the feasibility and cost of the conceptual accelerator designs.

Acknowledgments

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ISOL- and In-Flight-based production of rare isotopes

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The main goal of nuclear physics is to unravel the fundamental properties of nuclei composed of a finite number of strongly interacting fermions of two kinds that constitute its building blocks called nucleons: the protons (Z, the charge) and the neutrons (N). Three of the four interactions in nature, the strong, the electromagnetic and the weak forces, are at play in the nuclear system. The strong interaction in the nuclear medium cannot be treated perturbatively and the number of nucleons is not large enough for the use of statistical methods. Although large progress has been done in the recent time with ab-initio calculation to describe the nuclear behavior from first principles, so far, we do not have a theory able to describe the nuclear mesoscopic system from light to heavy nuclei. It is vital to achieve a thorough understanding of the complex structure of nuclei and the nuclear reactions in our laboratory and be able to induce their behavior in astrophysical scenarios. In addition, nuclei also constitute a unique laboratory for a variety of investigations of fundamental physics, which in many cases are complementary to particle physics. Large experimental and theoretical efforts are made world-wide to address the open questions of nuclear physics. Following the 2017 European long-range strategy these questions were formulated as: How does the complexity of nuclear structure arise from the interaction between nucleons? What are the limits of nuclear stability? How and in which astrophysical scenario are the chemical elements produced?

In order to address and progress the answer to these questions the scientific community is continuously developing new and more sophisticated tools at the level of accelerators and detectors. Research with radioactive ion beams has in the last decades entered in a new era with the advent of energetic beams of radioactive nuclei.

In 1919 Ernest Rutherford was the first to transmute one element into another. He observed the production of hydrogen by sending alpha articles into nitrogen gas. In 1932, John Douglas Cockroft and Ernest Thomas Sinton Walton repeated this experiment using an accelerated alpha beam. They knew that in order to overcome the Coulomb barrier and produce reactions they would need energies of the order of MeV. They were the first to apply beams accelerated by a DC device to produce a nuclear reaction. Using known voltage-multiplication schemes they succeeded in carrying out cross-section measurements of proton and alpha induced reactions on a number of nuclei. This achievement was followed by an impressive development in accelerator technology.

From the early years of nuclear science, it was clear that the radioactive decay of nuclei into their descendants, isobar or alpha-daughter, closer to stability was a source of identification of new species as well as to obtain information of their nuclear structure. The information was limited to the descendants of the different natural radioactive nuclei. The first radioactive nuclei, ^{13}N and ^{30}P, produced by reaction on two stable ones, aluminum (^{27}Al) and boron ($^{10,11}B$), was obtained in 1934 by Irene Curie and Jean Frédéric Joliot. Enrico Fermi got the Nobel prize in 1937 by his "demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons". After four years of detailed studies by the chemists Otto Hahn and Fritz Strassmann and the physicist Lise Meitner, fission was discovered in 1938, when barium was identified by bombarding uranium with neutrons. Lise Meitner and her nephew Otto Robert Frisch gave the physics interpretation of this reaction process. The first fission reactor was built by Enrico Fermi in Chicago in 1942 based in the use of uranium oxide and graphite as neutron moderator. It went critical 2nd of December 1942 demonstrating the first laboratory-created nuclear chain reaction. This was the beginning of the identification and study of many neutron rich radioactive nuclei produced in neutron capture reactions. All isotopes of the chemical elements can be organized in a two-dimensional plot referred to as the Nuclear Chart.

For the exploration of the nuclides in the nuclear chart advances in accelerator techniques has been crucial. For more details and many more references, I recommend the review paper [1].

First light-ion and later on heavy-ion induced fusion reactions were used for the production and study of new isotopes. In particular heavy-ion reactions are very successful in exploring the unknown territory due to the specific N/Z dependence of the line of stability. Most combinations of stable projectiles and targets produce neutron-deficient nuclei in the region of heavy masses. These reactions are rather selective with only a limited number of channels. This is an important difference with respect to the spallation, fragmentation and fission reactions where hundreds of nuclei may be produced. The question is how to isolate one of the scarcely produced short lived species from the overwhelming production of the other nuclei closest to the valley of stability. The ISOL-method and the In-Flight are two complementary techniques to achieve this goal. Both methods transport the produced species to a lower background zone where the nuclear properties are explored in an adequate experimental setup.

The final aim of the different facilities is the production of exotic beams, usually called Radioactive Ion Beam (RIB), as intense and pure as possible. For that we need to achieve the highest production rate, an efficient manipulation of the reaction products, fast delivery as we are dealing with short-lived species and high selectivity. These are therefore the figures of merit of the facilities dedicated to the production of nuclei. In the following we will give a short description of the two methods and the different facilities presently using them as well as a short description of the plethora of upgrades of existing as well the new facilities in construction.

The ISOL-Method

In 1951, a novel method of studying exotic nuclei was developed, by bombarding an uranium target with fast neutrons coming from the breakup of a 11 MeV deuteron beam. Noble gases were produced by fission, after thermalization in the target they were ionized and electromagnetically separated [2]. The full process of production, ionization, mass separation and implantation in the detector setup for their study was done in a continuous way. With this the so-called Isotope Separation On Line (ISOL) technique was born. Along the years, tremendous efforts have been dedicated to produce and separate a large variety of beams by the combination of many materials for the targets and different design of ion sources. In the ISOL method the radioactive products are thermalized in the target and then re-accelerated. The resulting beams have an emittance, energy resolution and time structure of excellent quality. But the thermalization process and the re-ionization are slow processes in the range of ms to s leading to severe losses for short-lived nuclei and can be very inefficient for refractory elements. These problems can be mitigated if the slowdown process occurs in gas catcher leaving the ions in a 1^+ state. This method has been successfully demonstrated in IGISOL (Ion guide Isotope Separator On-Line) the heart of the Facility at JYFL, Finland. Besides the excellent optical quality of the low energy radioactive beams, the possibility of using a thick target increases the production considerably and it has allowed for the detailed study of exotic nuclei down to ms half-life, in spite of the losses in the target. Studies of ground and isomeric state properties in the same element, probe of fundamental interactions and exotic decay modes are performed for many nuclei. The intensity of the produced beams is directly proportional to the cross section times the intensity of the incoming beam times the number of atom exposed times the efficiency ($Y = \sigma \times I \times N_t \times \varepsilon$). This efficiency is the product of the efficiencies for diffusion, effusion in the target, the ionization process, mass separation and transport .The figures of merit of this type of installation are: intensity of the primary beam, fast release of the target products, sensitivity and selectivity. The success of radioactive beams produced in ISOL facilities triggered the interest in producing post-accelerated low-energy beams to energies up to Coulomb barrier and even beyond for reaction studies of, for instance, astrophysical interest. However, the realization of this dream had to wait until 1989, when, for first time, in Louvain-la-Neuve the first post-accelerated beams were produced by coupling the two cyclotrons with an isotope separator, and the astrophysical interesting proton capture of ^{13}N was studied up to energies of 0.63 MeV/u [3]. A picture of the principle of the ISOL method with the main elements is given in figure 1.

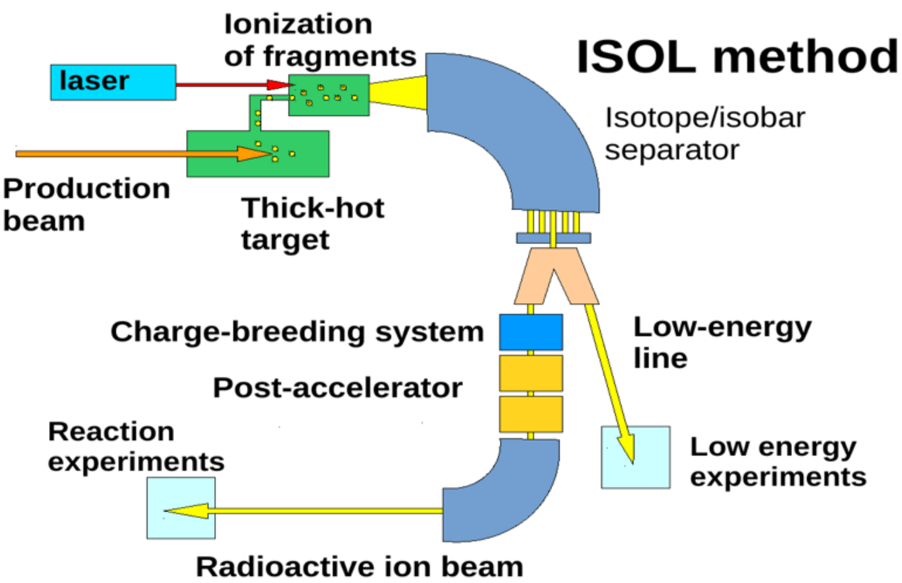

Figure 1 A schematic view of the main elements of the ISOL-method is shown. The RIB production depends on the energy and intensity of the primary beam and the choice of target and ion source for chemical selectivity and fast release. The shortest delivered nuclei have a half-live in the ms-range. The isotope mass separator will help to deliver pure taylor-made species to experiment.

Presently, there are three major ISOL facility in the World producing a large variety of beams, two in Europe CERN-ISOLDE and GANIL-SPIRAL and TRIUMF in North-America. One of the first facilities developing the ISOL concept and still the one with the largest variety of beams is ISOLDE. This Facility continuous pioneering new devices to stay at the forefront of nuclear studies, as it is summarised in the focus issue on exotic beams written to commemorate its 50th anniversary [4]. ISOLDE makes use of the high energy and intensity of the proton beam from the CERN accelerator complex impinging on a large variety of thick targets including uranium carbide. Different types of ion sources are available, surface, plasma and resonant ionization Ion sources (RILIS). The latter is element and even isotope selective assuring high purity beams. The beams extracted from the ion source up to a voltage of 60 kV are further purified by the use of a mass separator. Since 2001 post-accelerated beams are available and more than one hundred different beams were used for experiments. In 2018 the energy upgrade to 10 MeV/u was accomplished as part of the high Intensity and energy upgrade of the facility, the HIE-ISOLDE.

The TRIUMF Isotope Separator and Accelerator (ISAC) facility uses a 500 MeV proton beam of up to 100 µA intensity steered onto one of two production targets to produce radioactive isotopes that are sent to the low-energy beam transport (LEBT) electrostatic beam line and sent via a switchyard to either the low-energy experimental area in the ISAC-I facility or to a series of room-temperature accelerating structures in the ISAC-I medium-energy experimental area. For high-energy delivery, the drift tube linac (DTL) beam is deflected along an S-bend transfer line to the ISAC-II superconducting linear accelerator (SC-linac) for acceleration above the Coulomb barrier (5-11 MeV/u). The continuous improvement of the RILIS ion source together with the recent license for the use of uranium carbide targets bombarded at higher and higher intensity (with permission go up to 40 micro-Amp) have led to the production of many new elements and a substantial increase of the intensities delivered.

The SPIRAL1 facility makes use of the GANIL coupled cyclotrons as a driver to produce heavy ion beams to impinge on a thick graphite target. The fragmentation products are ionized in a permanent magnet electron cyclotron resonance (ECR) ion source. This scheme is very simple but limited the production to noble gases plus oxygen and fluorine nowadays enlarged by the use of surface and FEBIAD ion sources to include the alkali and alkali-earth elements. These beams can be post-accelerated using the CIME cyclotron that also serves as high resolution mass separator of the radioactive beams accelerated up to 20 MeV/u, the highest of the current ISOL facilities.

The Ion Guide Isotope Separator On–Line (IGISOL) facility, operating in the JYFL Accelerator Laboratory, Jyväskylä, produces low–energy beams of radioactive isotopes in a universal manner employing the ion guide technique. This installation has gained recognition by their pioneering work. For instance, a new radiofrequency heated graphite catcher combined with in–source resonant laser ionization has produced neutron–deficient Ag isotopes.

The In-flight Method

The so-called In-flight facilities are highly successful in exploring the limits of nuclear stability due to the fast delivery of exotic nuclei from the production to the experimental setup, high transmission and good particle identification. The nuclei will be produced mainly by fusion, fission and fragmentation. The in-flight approach profits from the kinematics of the reaction producing the radioactive isotopes to separate them. This makes the process very fast facilitating to explore nuclei with extremely short half-life. When inducing, for instance, fission of a heavy nucleus, the two fission products have energies around 100 MeV, if the target is thin enough the fission products will recoil out of the target in a charged state. The conservation of mass and momentum in fusion and fragmentation reaction of heavy ions in light targets made the reaction products to be emitted forward in the beam direction. Thanks to the use of a powerful electromagnetic system called fragment separator combined with degraders where the energy losses depends of the atomic mass or with gas section where velocity focusing takes place, the reaction products can be separated from the incoming beam and a separation of the produced species in A and Z is obtained. This method was pioneered at the Bevalac at Berkeley where, in order to accelerate heavy ions to relativistic energies, they connected the super-HILAC heavy ion linear accelerator with the bevatron, a synchrotron accelerator half-mile away, in this way, they could study the fragmentation of a 1 GeV/u ^{20}Ne beam. Its real impact became clear with the measurements of the total interaction cross section of light elements [5] that lead to the discovery of halo structure. Due to the broad scientific opportunities the major high energy heavy ion facilities built in the eighties-nineties: GANIL, GSI, NSCL-MSU and RIKEN dedicated more and more of their beam time to radioactive beam production (RIB). The method is schematically shown in figure 2.

The GANIL driver consists of two room temperature cyclotrons that produces heavy ions from C to Ar up to 100 MeV/u and accelerate heavier beams up to U to 25 MeV/u. High primary intensities of several micro-Amp can be delivered but the final RIB intensities are limited by the relatively weak forward focusing at intermediate energies. This facility has the lowest intermediate energy. To improve the overall efficiency an ingenious superconducting solenoid, SISSI, was placed after the production target yielding an increase of RIB of a factor of 100. This device stopped working in 2008, limiting the RIB production to the doubly achromatic LISE (Ligne d'Ions Super Epluchés) spectrometer This spectrometer of maximum rigidity of 3.2 Tm is able to deliver radioactive beams with good energy resolution and a small amount of contamination for beams close to the projectile mass. Many light nuclei have been studied in this facility that pioneer several experimental devices. Production and selection efficiencies are larger at NSCL-MSU and RIKEN where the fragments separators A1900 and RIPS were specifically built for efficient RIB selection.

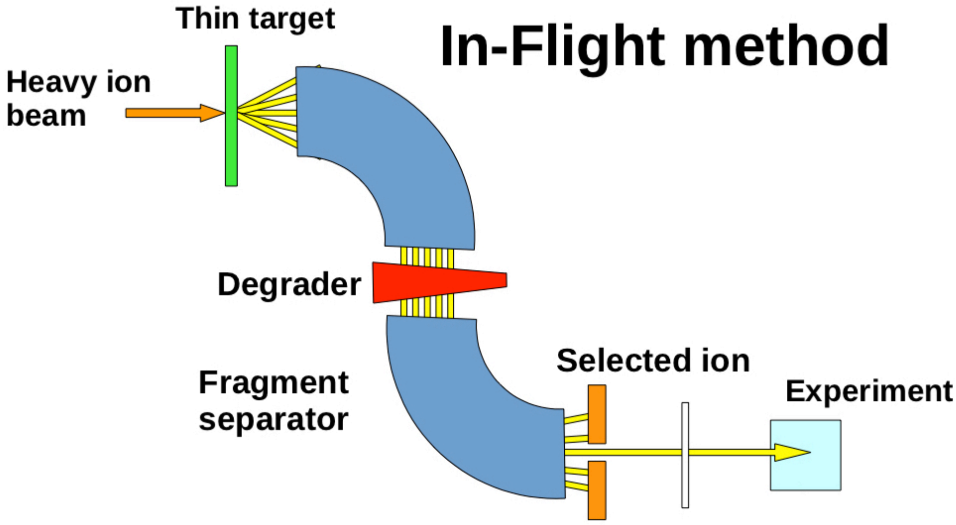

Figure 2. Schematic view of the In-Flight method to produce RIB. The advantage of this method are the chemical blindness and the very fast delivery that allow the delivery of the very short-lived species. To preserve the kinematic focusing the target have to be thin what limits the intensity of the produced nuclei.

The NSCL-MSU facility uses two coupled super-conducting cyclotrons with K=500 and 1200 MeV. It is a unique facility with in-flight separation, stopping, and since September 2015 with reacceleration of rare isotopes at ReA3. The first rare-isotope beam produced by the coupled cyclotrons, separated with the A1900, thermalized in N4, charge-bred in the EBIT and then reaccelerated by ReA3 was used to carry out an experiment with the active target time projection chamber (AT-TPC). More than 900 beams of different nuclei have been used for experiments up to antimony (Z=51). The A1900 is a third-generation projectile fragment separator composed of 40 large diameter superconducting multipole magnets and four 45° dipoles with a maximum magnetic rigidity of 6 Tm. The A1900 has large solid-angle, acceptance of 8 msr, a momentum acceptance of 5.5%, and can accept over 90% of a large range of projectile fragments produced at the NSCL. The cyclotrons will stop operation at the end of 2020 in order to couple to FRIB. During the transitional period the ReA3/6 will possibly be operative.

The GSI Facility combines a high intensity Universal linac commissioned in 1975, UNILAC, accelerating ions from 2-11.4 MeV, with the heavy ion (Schwer Ionen) Synchrotron, SIS18, added in 1990 that allows for acceleration of ions up to 2 GeV/u, boosting the energy of the ions from 10% to 90% of the speed of light. Furthermore, the facility incorporates also the fragment separator, FRS, and the experimental storage ring (0.005-0.5 GeV/u), ESR. This has facilitated the first study of reactions in full kinematics at in-flight facilities. Although the intensity is less than the one produced by cyclotrons it is partially compensated by the high energy of the incoming beam that produces larger forward focusing of the reaction products and the high efficiency of the fragment separator.

The radioactive Ion Beam Factory (RIBF) at RIKEN, Japan couples since 2007 four cyclotrons between the old ring cyclotron (k570 and fixed frequency ring cyclotron) and a new facility that includes the intermediate ring cyclotron and the Superconducting ring cyclotron, SRC K2600 obtaining intense, up to 80 kW, heavy ion beams with light ions accelerated up to 400 MeV/u and up to 345 MeV/u for a uranium beam. This facility has taken the lead as part of the "next generation" of in-flight facilities delivering in 2007 the most intense ^{48}Ca beam of 200 particle micro-Amp and with continuous improvements aiming to reach micro-Amp intensities of uranium beams. A super-conducting fragment-separator, BigRIPS, is used for selecting the radioactive beams.

To profit from the best of in-flight and ISOL facilities in the quest to achieve high quality beams of short-living radioactive ions one can slow down the fast-radioactive beam in a gaseous catcher leaving the beam in a 1^+ charge state. This is the aim of for instance, the SLOWRI ring. The construction started in 2013, SLOWRI builds on two kind of gas catchers, He gas catcher with RF carpets for ion guide and Ar gas catcher with resonant laser ionization. The precise mass measurements of trans-uranium elements have been successfully performed using the SLOWRI prototype and multi-reflection time-of-flight mass spectrograph (MR-TOF). First results in the region of Z=100 have already been published [6].

Figure 3 shows the evolution of discovery of nuclei plotted on the two-dimension nuclide chart with protons on vertical axis and neutrons on the horizontal one. The grey background corresponds to the possibly existing nuclei. The chosen years for display correspond to the start of the ISOL-method, the use of in-Flight method by different facilities and present situation.

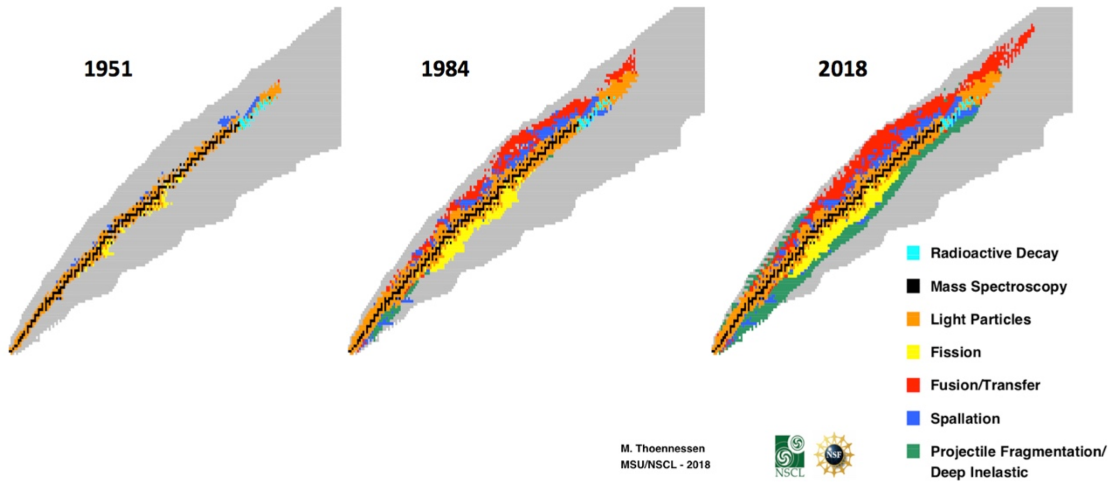

Figure 3 The two-dimension plots with protons on y-axis and neutron on x-axis, courtesy of M. Thoennessen, shown in grey the expected nuclei. On the left plot, the nuclei known prior to the use of the ISOL-method where reaction with light particles and some spontaneous fission allow for the production of the 900 nuclei known. The central plot shows the 2257 nuclei known prior to the use of in-flight method. Neutron deficient nuclei were produced by fusion-evaporation, fission, fragmentation and spallation in thick targets. The nuclei chart on the right shows the situation in December of 2018 with 3302 nuclear species identified [7]. The advancement into the so-called "Terra Incognita" thanks to the in-flight facilities is outstanding.

Future Facilities and Upgrades:
In the following I will mention the new facilities and upgrades. As each facility mixes different techniques in the quest to explore and characterize the limits of the nuclear chart towards higher mass numbers, they will be described in alphabetic order.

The **Advanced Rare Isotope Laboratory (ARIEL)** at TRIUMF. The ISAC facilities will be enlarged and complemented with ARIEL including an electron-linac. The targets will be bombarded either with protons or electrons allowing for a multiuser facility at the maximum intensity per rare isotope. The operation of the three production stations will allow to fully exploit the numerous existing experimental devices at ISAC. At the heart of ARIEL is a superconducting electron accelerator (e-linac) for isotope production via photo-production and photo-fission as well as a second proton beam line from TRIUMF's cyclotron for isotope production via proton-induced spallation, fragmentation, and fission. The e-linac was built and produced the first accelerated electron beam in 2014. They have implemented and made operative in 2019 the high-resolution mass separator. In order to have a wider range of post-accelerated beams an EBIS charge breeding device has been built and will be used for physics in 2020. The target design to stand the full power is progressing well. The facility will produce first science with the e-linac in 2023 and the three parallel RIB will be operative in 2026.

FAIR (Facility for Antiproton and Ion Research) located by GSI is the most ambitious nuclear physics project in construction in Europe. The research at the facility includes four pillars: physics of hadrons and quarks in compressed matter (CBM). Hadron structure and spectroscopy, strange and charm physics with anti-protons (PANDA), Atomic, Plasma Physics and Applications (APPA), and the one of interest here for the structure of nuclei, physics at NUclear Structure and Astrophysics research with RIB (NUSTAR). The core of FAIR is the new superconducting synchrotron SIS100 with magnetic rigidity of 100 Tm and circumference of 1100 meters which will deliver high intensity primary beams of 10^{12} ^{238}U at 1.5-2 GeV/u, two to three orders of magnitude higher intensity than the SIS18. The heart of NUSTAR will be the new fragment separator Super-FRS that will improve the transmission and efficiency over a broad range of masses. An increase of a factor of ten thousand in intensity with respect to current GSI production is expected. The existing GSI accelerators UNILAC and SIS18 will serve as injectors to SIS100. Attached to SIS100 there is a complex system of storage-cooler rings and experimental stations. The beams can be used directed for reaction studies in R3B (Reactions with Relativistic Radioactive Beams), degraded to low energies to do High-resolution in-flight SPECtroscopy studies with AGATA and other cutting-edge devices in HISPEC and fully stopped for the decay spectroscopy studies (DESPEC), mass measurement (MATS and ILIMA) as well as radii and moments measurements by laser spectroscopy (LASPEC). All these activities are part of the modularized start version that should be operated in 2025.

The Facility for Rare Isotopes Beams (**FRIB**) builds upon the expertise and earlier achievements of the National Superconducting Cyclotron Laboratory (NSCL) at MSU. Since 2001, NSCL's coupled cyclotron facility has been conducting experiments on rare isotopes. FRIB looks beyond NSCL to envision the use of fast, stopped, and reaccelerated rare isotope beams produced by fragmentation to yield consistently high intensities of beams in minimal beam development times. The driver of FRIB will be a 400 kW Linac delivering beams up to 200 MeV/u. The technical construction started in 2014 and the civil construction is also complete. The FRIB fragment separator should be able to accommodate 400 kW and allow ion-by-ion identification. It will have three stages, one high power pre-separator and two high resolution parts for production and delivery of exotic beams. It will have fast, slow with ReA6 and stopped beam experiments. It will start the experimental program in 2022.

HIAF: The Heavy Ion Research Facility at Lanzhou (HIRFL), in Lanzhou, China, is a facility focusing on nuclear physics, atomic physics, heavy ion applications and interdisciplinary researches. Based on the developments and experience with heavy ion beam accelerators, a new project HIAF was proposed in 2009. The facility is being designed to provide intense primary and radioactive ion beams. The HIAF project consists of ion sources, linac accelerator, synchrotrons and several experimental terminals. The Superconducting Electron-Cyclotron-Resonance ion source (SECR) is used to provide highly charged ion beams, and the Lanzhou Intense Proton Source (LIPS) is used to provide H_2^+ beam. The superconducting ion Linac accelerator (iLinac) is designed to accelerate ions with the mass to charge ratio, A/q = 7 (e.g. $^{238}U^{34+}$) to an energy of 17 MeV/u. Ions provided by iLinac will be cooled, accumulated and accelerated to the required intensity and energy (up to 1×10^{11} and 800 MeV/u of $^{238}U^{34+}$) in the Booster Ring (BRing), then fast extracted and transferred either to the external targets or the Spectrometer storage Ring (SRing). An electron target with ultra-low temperature electron beam will be built for Dielectronic Recombination (DR) experiments. Both stochastic cooling and electron cooling systems are going to be incorporated in order to provide high quality beams for experiments. Highly purified radioactive beams can be extracted from SRing for nuclear physics experiments.

HIE-ISOLDE at CERN: In order to broaden the scientific opportunities of ISOLDE far beyond the present scientific opportunities. The HIE-ISOLDE project provides major improvement in the energy of the post-accelerated beams as well as in the intensity, selectivity and quality of the exotic beams. The project started in 2010 with the design of a super-conducting Linac to be connected to the existing REX-LINAC. The first cryomodule was installed and the first experiment realised in 2015. The energy upgrade including four cryomodules was operative in 2018 reaching energies of 9.5 MeV/u for A/q = 4.5. Acceleration of more than one hundred different beams has been obtained over the years. The intensity upgrade will profit from the new CERN injectors, LINAC4 that will start operating in 2021 and the increase of energy to 2 GeV of the proton beam of the CERN-PSB (Proton Synchrotron Booster). The higher energy of the proton beam will increase the fragmentation and spallation reaction rate by a factor of 2 to 10. With the increase of Intensity in a factor of 4, a global factor up to 40 can be expected for the production of certain species. This increase in power on target require new beam dumps, further, a new dipole magnet to transport the p-beam to ISOLDE that will take place in the next CERN technical stop in 2024. The improved beam quality and purity depends on different advances some of them already implemented as the solid-state lasers of the RILIS ion source and the RFQ cooler, ISCOOL. Pending is the addition of a second experimental hall to host a new target-ion unit connected to cooler and a high-resolution mass separator. An extension of the existing hall to allocate a storage ring connected to HIE-ISOLDE is also foreseen.

ISOL@MYRRA: The Belgian atomic energy center, SCK-CEN, is actively working on designing, developing and realizing a multifunctional research installation in Mol. MYRRHA is an innovative accelerator driven system that consists of a subcritical nuclear reactor driven by a high-power proton accelerator (600 MeV, 4 mA). In 2008 the idea was proposed to use part of the proton beam to produce intense high purity radioactive ion beams: ISOL@MYRRHA. ISOL@MYRRHA will mainly focus on experimental programs needing long beam times in order to achieve sufficiently-high statistics in precision experiments or to hunt for very rare phenomena. In 2018 the Belgian government decided to support the construction and exploitation of the first phase of the MYRRHA project, as well as the further development of subsequent phases. Phase I comprises a single-injector (500 micro-Amp, 100 MeV) LINAC, MINERVA, and a proton target facility of ISOL type. The construction of this ISOL target station, with all required infrastructure will mark the starting point of the realization of ISOL@MYRRHA phase I that should have first beams in 2026 reaching full operation in 2027 when the first ISOL beams will be produced.

The Radioactive Ion Beam Factory (**RIBF**) is in continuous evolution with its three injectors: RIKEN heavy-Ion Linac, RILAC operative since 1980, AVF from 1989 and RILAC2 from 2011. The energy is boosted by four ring cyclotrons, the RRC, K540 and the fixed frequency Ring Cyclotron (fRC) K570 from 1986. In 2006, the fRC was upgraded to K700 and two more were added, Intermediate-stage Ring Cyclotron K980 and the Superconducting Ring Cycclotron K2400. This complex conforms the so-called new facility, together with BigRIPS, more details can be read in [8]. The fragment separator, BigRIPS is characterized by two major features: large acceptances and a two-stage separator scheme. The large acceptances are achieved by the use of superconducting quadrupoles with large apertures. This feature enables efficient RI-beam production, even when the in-flight fission of uranium beams at 350 MeV/nucleon is employed as a production reaction. The two-stage separator scheme allows one to deliver tagged RI beams: The first stage of BigRIPS separator serves to produce and separate RI beams, while the second stage serves to identify RI-beam species in an event-by-event mode. The steady increase of primary beam current over the years is plotted in figure 4. In the near future, it is planned to increase the intensity of the Uranium beam by a factor of ten or more. Key to the improvement is the ion source, and losses in the acceleration. To reduce the losses in the charge stripper (a foil) an innovative solution will be realized involving a charge stripper ring. The beam will circulate by the stripper ring until it reaches the required charge state. If successful a factor of ten improvement is expected. They also expect to reach with other improvements in the up to 2000 pnA. In the exploration of superheavies it is planned to build a Super-Rilac for injection.

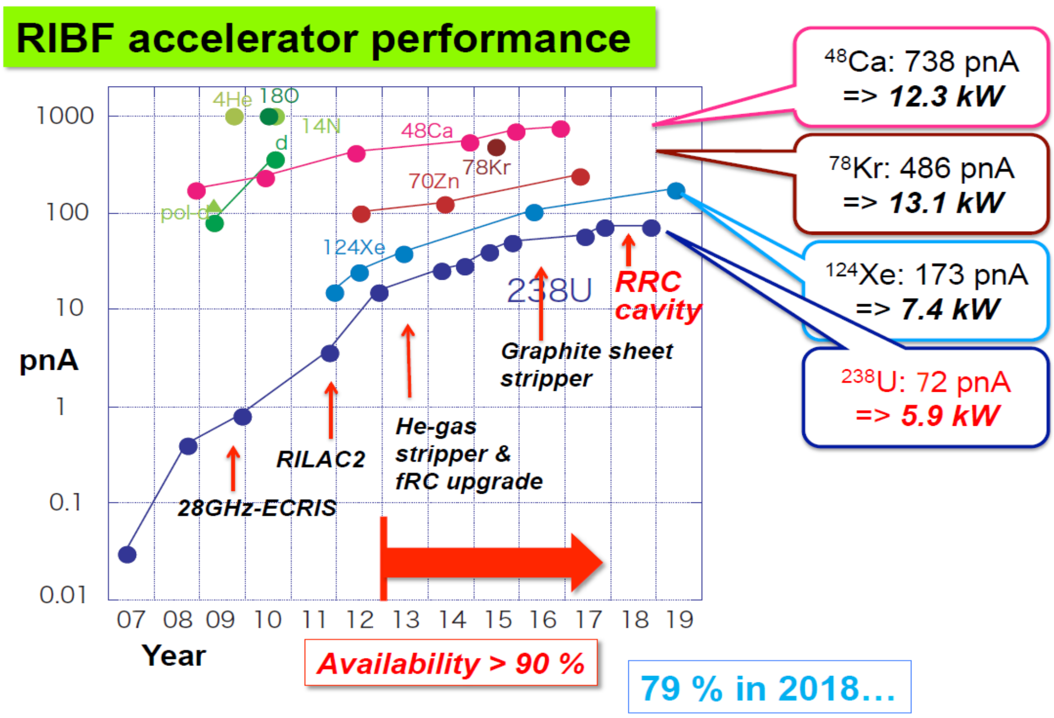

Figure 4. Steady grow of the primary beams in RIBF. The increase and availability of different beams is associated with the improvements of different parts of the machine: ECRIS Ion source, RILAC2, different strippers and in the Riken Ring Cyclotron complex.

Korea is building from zero a large facility: Rare Isotope Science Project (**RISP**). It is constructing equipment and facilities for the Rare isotope Accelerator complex for ON-line experiments (RAON). RAON is a large basic science research facility built around a heavy-ion accelerator. The heavy-ion accelerator is aiming to produce new rare isotopes by greatly accelerating and then protons or heavier ions into targets. RAON will combine the ISOL and In-flight Facilities in the same site for the production of rare nuclei. RAON is a very ambitious project since cutting-edge superconducting radio frequency (SRF) technology is used to form the entire linear accelerator systems.

SPES (Selective Production of Exotic Species): new mid-term facility dedicated to the production of neutron-rich nuclei by fission. It will have a 70 MeV cyclotron as proton driver with two ports for a total current of 750 micro-Amp. One of the ports will be used for production of medical isotopes and the other for ISOL- production. They will use a Uranium Carbide target, ion source and a high-resolution mass separator. The superconducting PIAVE-ALPI accelerator has been upgraded and will be used as radioactive beam re-accelerator. A similar cyclotron has been purchased at i-Themba Labs in South Afrika for production of medical isotopes leaving the existing SSC for nuclear physics. The ISOL system will start working at the end of 2021 and the UCx target will be operative in 2022.

SPIRAL2 at GANIL: The aim here is to have a multi-beam driver in order to allow both ISOL and low-energy in-flight techniques. The driver of SPIRAL2 facility is a high-power continuous wave (CW) superconducting LINAC delivering up to 5 mA of protons up to 33 MeV and deuterons at 40 MeV and heavy ions up to 14.5 MeV/u. The construction of a new injector for the SPIRAL2 Linear Accelerator is planned in order to expand the range of available high-intensity beams up to Uranium. The heavy ion beams will be used to produce in-flight nuclei with the Super Separator Spectrometer (S3), neutron-deficient exotic nuclei and very heavy nuclei via fusion evaporation reactions. Light neutron rich nuclei will be produced via transfer reactions. The low energy exotic nuclei (few keV/u) produced at S3 and at the existing SPIRAL1 facility will be studied in the new experimental hall DESIR (Decay, Excitation and Storage of Radioactive Ions). The high neutron flux produced by the deuteron beam will be used at the Neutron for Science facility for applications and reliable nuclear data evaluation. While writing these lines I got the good news that the proton beam at the SPIRAL2 LINAC has been accelerated to its nominal value in November 2019. The facility will be in full swing in 2021 reaching the expected maximum power of 200 kW. The main goal will be to study the limit of existence and the structure of nuclei in unexplored middle and heavy mass regions of the chart of nuclei. The DESIR hall will be ready for experiments in 2024.

Superheavy factory (**SHE**) in Dubna, Russia. The production of superheavy elements uses fusion reactions. Both cold and hot fusion has allowed to reach the heaviest elements from Z=106 to Z=118. The heaviest elements have been produced in GSI (Germany), RIBF, RIKEN (Japan), and JINR FLNR in Dubna (Russia). The success in using hot fusion with ^{48}Ca beams to synthesize the heaviest elements known has prompted the construction of a new facility dedicated only to the study of superheavy elements. The factory is based on a high intensity cyclotron DC-280 that was commissioned in March 2019 and that should start operation in December 2019. A factor of ten in intensity is expected. It will operate as a stand-alone machine able to accelerate ions from carbon to uranium up to 4-8 MeV/u.

A totally different approach is taken by the facility being built in Romania the **ELI-NP**: Extreme Light Infrastructure - Nuclear Physics facility that will operate two components: (i) A very high intensity laser system, with two 10 PW laser arms able to reach intensities of 10^{23} W/cm^2 and electrical fields of 10^{15} V/m. (ii) A system with maximum gamma energy of 19.5 MeV with spectral density: 10^4 ph/s/eV and ~ 0.1 % bandwidth. For the production method the photons scatter on high energy electrons. ELI-NP will allow both combined experiments between the high-power laser and the gamma beam and stand-alone experiments with nine experimental areas. In March 2019, ELI-NP has reached the highest laser power level ever produced on Earth. In December 2019, they will perform measurements with tera-watt photon beam ramping up the power to be able to do experiments in June-July 2020 with 10 PW. The experiments with the gamma beam will have to wait until 2023.

Summary: In this contribution I have summarized the existing and planned large nuclear physics facilities. The production of new exotic nuclei and its study is essential to advance the field. The nucleus is a multibody system that has many facets. One nucleus is not important enough to drive the field. Systematic studies on the evolution in N and Z have built-up and driven the field. The present and future of RIB science is very bright, I do not think it has been a time ever when so many facilities are simultaneously operative, being upgraded or under construction. Many of the above described facilities will be fully operative in 2025. These efforts are driven by the scientific potential of RIB and have been matched by similar developments in instrumentation which description is beyond the scope of this contribution. RIB became the workhorse for nuclear structure and reaction studies helping us to unveil the nuclear interaction in matter and have also become an essential part of nuclear astrophysics. The recent proof of one of the r-process production scenarios, the neutron star mergers, via multi-messenger identification gives extra pressure in the production, identification and determination of fundamental properties of neutron-rich nuclei along the r-process path. Different facilities and experimental techniques need to be applied to solve a specific problem. The progress in Nuclear Physics presents a wide front to elucidate the nucleon-nucleon interaction and all phenomena it can produce. The complementarity of the methods is important. The operation of these new facilities will increase the present rate of discovery of fifty new nuclei per year. At this rate, we will need up to 66 years to produce all the possibly existing nuclei. In this long way, new and unexpected phenomena will appear. The efforts in the coming years on the RIB Science will keep the field of nuclear physics at the forefront of modern fundamental research and will open new opportunities for technical, environmental and medical applications.

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Neutrinos and Nuclear Physics

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1 Introduction

Neutrinos are ubiquitous: they were produced in the earliest moments of the Universe, they are created nuclear decays, accelerator beams, in the crust of the Earth, in stars like the Sun and supernovae, in interactions of high-energy cosmic rays with the Earth's atmosphere and in the hearts of active galaxies. With such a broad range of energies and sources, and with the intrinsic difficulty of detecting them, detectors built to observe neutrinos and measure their properties span an enormous range in technologies and methodologies, from small-scale solid state detectors to instrumented kilometer-scale sections of ice or water.

Nuclear physics has played a critical role in many of the most important neutrino measurements that have been made, and that are yet to come. But neutrino properties themselves are field- and methodology-agnostic; one can measure the same neutrino mixing parameters using neutrinos produced in nuclear reactors or high-energy accelerator beams or from the Sun. Yet some areas lie clearly within the domain of nuclear physics either because their methodological approach has grown out of the nuclear physics community, or they relie heavily on input from nuclear physics (or provide direct output to issues relevant to nuclear physics), or they depend upon nuclear theory.

With this distinction in mind, the neutrino areas that most relevant for this discussion are searches for neutrinoless double beta decay, observations of neutrinos from the Sun and stars, neutrino interactions with matter, measurements of reactor antineutrinos, and direct mass measurements of neutrinos. The focus here will be on the first three; reactor antineutrino measurements are extremely important and recent direct mass measurements made by the KATRIN collaboration [1] are very beautiful, but including these here would require a lengthier document.

2 Neutrino Questions

Measurements over the past two decades have established that the three known flavors of neutrino ν_e,ν_μ, and ν_τ, are massive and mixed into three "mass eigenstates" ν_1,ν_2, and ν_3, with a three-flavor unitary mixing matrix parameterized by three angles and a complex, CP-violating phase δ. Unlike the quark sector, where mixing is small, neutrinos have two large mixing angles (θ_{23} and θ_{12}), and one smaller one (θ_{13}). Oscillations are controlled by the difference in the neutrino masses squared, $\Delta m^2_{ij} = m^2_i - m^2_j$, with measurements of $\Delta m^2_{12} \approx 7.5 \times 10^{-5}$ eV^2 and $|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}$ ev^2.

While values of the mixing parameters and Δm^2s are known, there remain many critical questions about neutrinos that are yet to be answered: the octant of the mixing angle θ_{23} is uknown, as that angle is buried inside the oscillation terms and so as yet there has been no handle on it; the *sign* of Δm^2_{23} is unknown and therefore we do not know which neutrino mass state is heaviest (sometimes referred to as the "mass hierarchy" or "mass ordering" problem); while we know the magnitudes of the Δm^2_{ij}s we do not know the absolute mass scale m_ν of even one neutrino; we do not know the value of the complex CP-violating phase δ.

More critically than all of these, however, is that, as neutral leptons, it is unclear how many neutrino states there really are. Electrons and other charged leptons have four: right- and left-handed negative states, and right- and left-handed positive states. The left-handed negatively charged states and right-handed positively-charged states couple both electromagnetically and via the weak interation. The other two couple only electromagnetically. Neutrinos, however, have only Standard Model weak interactions—we know of no *fundamental* difference between a right-handed neutrino state ν_R and a right-handed antineutrino $\bar{\nu}_R$: they have the same mass, the same charge, the same handedness. Were these distinct particles, the ν_R would be a strange object, as it is an electroweak singlet coupling only via the higgs (and with such a small mass, extremely weakly). To make ν_R and $\bar{\nu}_R$ distinct (or the ν_L and $\bar{\nu}_L$) would require promoting what is an accidental global symmetry of the standard model lagrangian to a local symmetry.

If neutrinos are instead Majorana particles, then $\bar{\nu}_R$ and ν_R are the same state. Such a situation would have big implications, as it could explain the origin of the matter/antimatter asymmetry of the Universe (with associated CP violation in the lepton sector). It might also provide a mechanism for the generation of neutrino mass via the 'see-saw' relationship, which postulates the existence of very heavy neutrino states that ultimately lead to the very light states we observe.

3 Neutrinoless Double Beta Decay

The only practical way to show that neutrinos are Majorana particles is through the search for neutrinoless double beta decay (NLDBD). 'Double beta decay' is possible for for a small set of nuclear isotopes, ${}^A_ZX \rightarrow^A_{Z-2} X + 2e^- + 2\bar{\nu}_e$. If neutrinos are Majorana particles, the process ${}^A_ZX \rightarrow^A_{Z-2} X + 2e^-$ is also possible. The rate of the 0ν process depends on a phase space factor ($G_{0\nu}$), a matrix element $|M_{0\nu}|$, and the effective neutrino mass ($m_{\beta\beta}$) squared:

$$\Gamma_{0\nu} = G_{0\nu}|M_{0\nu}|^2 m^2_{\beta\beta}. \tag{1}$$

Here, $m_{\beta\beta}$ is

$$m_{\beta\beta} = |\Sigma_i U^2_{ei} m_i| \tag{2}$$

$$m_{\beta\beta} = \cos^2\theta_{12}\cos^2\theta_{13}m_1 + \exp^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13}m_2 + \exp^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13}m_3 \tag{3}$$

and the angles θ_{12} and θ_{13} are two of the neutrino mixing angles, δ_{CP} is the complex phase in the mixing matrix that leads to CP violation in neutrino oscillations, and λ_1 and λ_2 are additional phases that are present if neutrinos are Majorana particles.

The relatively small value of θ_{13} in Eq. 3 means that if the heaviest neutrino state is m_3, the value of $m_{\beta\beta}$ will be small and the rate of NLDBD will be low, making experiments more difficult. An ordering of the masses that makes m_3 the largest of the mass states is usually referred to as the *normal* ordering. If, instead, m_2 is the heaviest state (solar neutrino results tell us that $m_2 > m_1$), then $m_{\beta\beta}$ can be as large as 50 meV or so, and the rate of NLDBD is much higher. More importantly, in this regime—usually referred to as the "inverted ordering"—there is a *lower limit* to $m_{\beta\beta}$ based on the known mixing angles and Δm^2s, which lies around 10 meV. Thus, an experiment that probes below this value could falsify the Majorana hypothesis (putting aside other sources of new physics), if it were known that the ordering was "inverted." If the ordering is "normal," however, the Majorana CP phases could conspire to make $m_{\beta\beta}$ extremely small. Nevertheless, there is a large fraction of parameter space in which a discovery of NLDBD could be made, well before this regime is hit.

There is no *a priori* expectation for what the ordering should be and, while the terms themselves are derived from the idea that like the quarks the masses of the neutrino flavor states should be ordered like the charged lepton states, and the mass states in turn should follow this ordering, the large mixing in the neutrino sector makes this guidance silly. A ν_3, for example, is nearly half ν_τ and half ν_μ, thus there is no reason why ν_3 should be "heavy like the τ is heavy."

Beyond the uncertainty associated with the unknown mass ordering (and the uncertainties in mixing angles), the interpretion of experimental results depends not just on an observed lifetime

Background Source	Primary Mitigations
$2\nu\beta\beta$ Decays	Energy resolution; long $2\nu\beta\beta$ half-life
"Internal" Radiological	Radiopure materials; analysis cuts
"External" Radiological	Fiducialization; radiopurity; analysis cuts
Cosmogenic	Depth; analysis cuts
Neutrino/Neutrino-genic	Size (smaller); cuts

Table 1: General sources of background in $0\nu\beta\beta$ seaches.

but, as shown in Eq. 1, on the phase space factor for the transition $G_{0\nu}$ and the matrix element, $|M_{0\nu}|^2$. The phase space is calculable, but $|M_{0\nu}|$ is very complex and difficult to calculate, and it varies dramatically between isotopes. Differences between different isotopes in $|M_{0\nu}|$ of factors of two or three are common and therefore lead to differences in the decay rate that can be almost an order of magnitude different. As an example, a experimental sensitivity using Ge of $T_{1/2} > 6\times10^{26}$y has a slightly worse sensitivity to $m_{\beta\beta}$ than does a $T_{1/2} > 2 \times 10^{26}$ y in Xe. Thus simply comparing sensitivities to half-life across experiments with different isotopes, does not necessarily convey the relative physics impact of each.

Unfortunately, the uncertainties on the matrix elements mean that comparisons of different isotopes are fraught with uncertainties that are themselves as large in some cases as the differences between the matrix elements. Thus comparing only by looking at the sensitivity to $m_{\beta\beta}$ is not such a good metric either. It is not unreasonable to compare experiments by the product of $T_{1/2}\times G_{0\nu}$ [2], because $G_{0\nu}$ is much more well known, but that loses the intuitive connection to the physics.

There is thus a great need for continued effort in the nuclear theory community, so that calculations can be improved and matrix elements become better known. Certainly a clear discovery of NLDBD would make this issue less pressing, but in the absence of such a discovery it is important to know "where we are" in terms of $m_{\beta\beta}$ sensitivity.

The importance of the question of the Majorana nature of the neutrino, combined with the uncertainties in its intepretation (ie, the matrix elements), and the difficulty of the measurement itself, have led to an explosion of beautiful techniques and experiments that draw from the rich history of nuclear physics experimental methodology. For all NLDBD experiments—and like all rare process experiments in general—sources of background are the critical driver. Table 1 lists the sources of backgrounds and their primary mitigation technique.

The current generation of experiments each align their approaches based on what they believe is the most dangerous background source and, of course, on the particular technology they prefer. The CUORE experiment uses TeO_2 bolometers, which have exceptional energy resolution thus rejecting the $2\nu\beta\beta$ backgrounds, and because they are grown crystals, they have very high intrinsic purity. The Ge-based GERDA and Majorana experiments (which have recently combined to form the "LEGEND-200" experiment), use Ge detectors which have both excellent energy resolution and high-precision pulse-shape rejection capabilities. EXO-200, which is a liquid xenon TPC, has excellent event topology identification and, because it is liquid, can purify and re-purify their isotope. Both KamLAND-ZEN and SNO+ use liquid scintillator "loaded" with a double beta decay isotope (Xe and Te respectively) and, because of their large sizes, exploit the ability to use high isotopic masses, strict fiducialization, and, like EXO, liquid purification.

The next generation of experiments is often referred to as the "tonne scale" but, in fact, a more useful metric is their targeted lifetime sensitivities—typically, they target $T_{1/2} > 10^{27}$y—or their targeted $m_{\beta\beta}$ sensitivity, for which they aim to get near to or below the bottom of the "inverted ordering" region. As discussed above, the differences in matrix elements and phase space for different isotopes, and the uncertainties in the matrix elements, makes neither lifetime nor $m_{\beta\beta}$ sensitivity by themselves useful absolute metrics for the next generation. As relative metrics, however—comparing the next generation to the current one—they are useful.

The international consensus is that the community should focus on at least one next-generation experiment, coalescing about a single "primary" isotope and technology. There is no consensus on which of the various approaches this should be. Competition for the next generation include upgrades to or new versions of most of the existing experiments, although CUORE would become CUPID, and likely use ^{100}Mo bolometers with additional light readout, instead of Te. The others are LEGEND-1000, which would be one tonne's worth Ge detectors; nEXO which would be 5 tonnes of enriched ^{136}Xe deployed as a LXeTPC; SNO+ Phase II wwhich would add additional natural Te to the existing detector to get to 2 tonnes of isotope; and KamLAND2-Zen which would deploy 1 tonne of enriched Xe in their inner scintillation volume and have improved light collection.

There are also next-next generation experiments already being discussed. These are all explicitly targeting the "normal ordering" regime, and include several new ideas. Theia would use a very large-scale liquid scintillator or water-based liquid scintillator detector to load tens of tonnes of Te or Xe, and reject solar neutrino backgrounds through the discrimination of Cherenkov and scintillation light. At 1 tonne, the CUPID detector would also reach the normal hierarchy regime. And NEXT-BOLD, a high-pressure gaseous Xe TPC which would be able to both identify the topology of the $\beta\beta$ event *and* identify the daugher Ba ion, would also push down into the 4-5 meV regime. The nEXO experiment has sensitivities that approach these in its 5 tonne version, and thus straddles “next generation” and “next-next generation.”

The process of down-selecting the next-generation experiments is ongoing, and while the physics sensitivities and discovery prospects of each approach weight heavily in the decision process, other factors may also come into play, such as the readiness of the collaborations and international participation, support of the community (it is likely that some consolidation of the field will be necessary), and possibly the breadth of the physics program beyond NLDBD.

4 Solar Neutrinos

The story of solar neutrinos and their role in the discovery of neutrino oscillations is a dramatic one, but one that is often told as if it has ended. In fact, solar neutrinos still present a rich area in which to study both neutrinos and our nearest star. As a neutrino “beam” solar neutrinos are background-free and begin in a well-determined flavor state. In some cases, the flux has been measured to precisions of better than 3%, and in some cases the flux is predicted to better than 1%. In addition, the effects of matter through the MSW effect are not only present, they are a huge, observable phenomenon. And, lastly, like the original vision for their observation, solar neutrinos tell us details about the Sun we cannot determine otherwise. Figure 1 shows a summary of the measurements of integral solar neutrino fluxes relative to their predicted values.

We now understand the energy dependence hinted at in the charged-current (CC) and elastic scattering (ES) measurements shown in Fig. 1 is caused by the matter or MSW effect. Matter is made of first-generation material and thus the ν_e component of the neutrinos has both CC and neutral-current (NC) interactions, while the other flavors have only NC interactions. Thus, the Sun is essentially birefringent to neutrinos, and this birefringence causes an additional transition between flavor states on top of the known vacuum oscillations.

Thus the solar neutrino sector is ripe for a precision measurement program, that can help search for both new physics, and new astrophysics. New physics may be found by using the MSW effect as a test of standard model interactions, and as a search for new, non-standard interactions. The MSW effect in the Sun leads to two very explicit predictions aside from the overall observed flavor transformation: that solar neutrinos passing though the Earth to a detector during the night will undergo additional matter-enhanced flavor transformation which results in an enhancement of the ν_e content compared to that during the day, and that there is a transition region between the high-energy (> 5 MeV or so) matter-enhanced flavor transformation in the Sun and the low-energy vacuum dominated oscillations that happen over the entire trip from solar core to Earth. Both the “Day/Night effect” and the vacuum/matter transition region are sensitive to new interactions

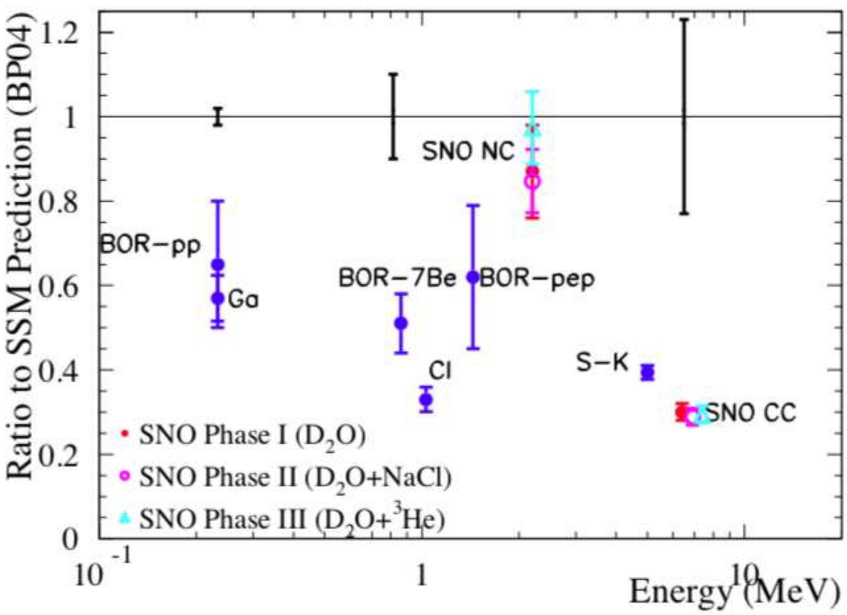

Figure 1: Summary of solar neutrino flux measurements as a function of energy threshold, compared to the standard solar model predictions.

of neutrinos with matter, and many models of these have been put forward, Interestingly, the measurement of Δm^2_{12} made by the solar neutrino experiments, and that made by the terrestrial KamLAND reactor antineutrino experiment (which is at best only weakly sensitive to the matter effect), are in tension at about the 2σ level. To resolve this tension will require new measurements both terrestrially (by experiments like SNO+ or JUNO), and by future solar neutrino experiments.

In addition to new neutrino physics, there are questions about solar astrophysics that could be resolved by future solar neutrino experiments. The production of energy in the Sun occurs via two distinct nuclear reaction chains. The more "famous" of these is the *pp* fusion chain, that leads to the production of the high-energy ^{8}B neutrinos detected by Super-Kamiokande, SNO, and Borexino (and the even higher-energy, and as yet unobserved, solar "hep" neutrinos) as well as lower-energy neutrinos like those from the primary *pp* process itself. The other chain is called the CNO cycle, in which carbon, nitrogen, and oxygen act as catalysts for the production of helium by hydrogen. While in the Sun the CNO cycle is responsible for only a small fraction of the energy the Sun produces, in higher mass stars it becomes the dominant reaction chain. Yet the CNO solar neutrinos have yet to be observed, in large part because they sit on top of radiological Bi backgrounds that are as-yet indistinguishable.

Observing the CNO solar neutrinos would have two interesting consequences: the first is that it would confirm the metallicity of the Sun. Early measurements of the surface metallicity of the Sun were used to help determine standard solar model predictions for helioseismologic measurements, and these measurements were in agreement with the model, leading many to begin trusting the predictions for solar neutrino fluxes. More recent measurements of the surface metallicity indicates that the Sun is in fact metal-poor, which in turn would mean the helioseismologic predictions were wrong and, hence, so were the neutrino flux predictions—which we now have *measured* to be correct. The conundrum could be resolved by measurements of the CNO neutrinos, which would directly tell us the metal content. Interestingly, it could be that both are right: as Haxton and Serenelli [3] have proposed, it might be that the Sun is metal poor on the surface and metal-rich in the core, and the surface appears depleted because the gas giants of the solar system "swept out" the metals from the original solar nebula. So the material accreted by the Sun in late stages of its formation was metal-poor, and that is what populates the surface.

Another precision topic for the Sun is whether we have accounted for all energy loss and energy-generating mechanisms. The *pp* neutrinos tell us the total rate of energy generation from mechanisms we know about (plus the CNO neutrinos). The solar photons tell us about all the energy that we see. Comparing the two luminosities in a precision way would test whether there is any additional energy we do not expect or any energy being lost (perhaps via new physics mechanisms). To date, the luminosity derived from the measurements of *pp* neutrinos is still not very precise, perhaps 10 times worse than their prediction (which is at the 1% level). Thus precision measurements of the *pp* neutrinos could tell us either about "new astrophysics" or new physics.

Lastly, as the solar neutrinos tell us directly about the core of our nearest star, it seems prudent that we continue to monitor them. While unexpected changes in the core are likely to take a long time to manifest themselves in a change in detectable solar luminosity, it would nevertheless be worth knowing that there are changes and trying to understand what their impact on life on earth might be.

There are several experiments either beginning or planned that could answer these questions. On the high-energy end, for ^{8}B and hep neutrinos, there are two new experiments that could have important solar neutrino sensitivity. The first is Hyper-Kamiokande, which will be a 200 ktonne water Cherenkov detector, and the other is DUNE. Hyper-K will aim to have more statistics than Super-Kamiokande did by its large size, and, with photocathode coverage high enough and radiological backgrounds backgrounds low enough, it could have a threshold of 3.5 MeV and then see the MSW transition region at 5σ in about 10 years. Although DUNE is smaller at 40 ktonnes, the fact that it is a LAr detector has a great advantage because of the high CC cross section on argon. As Capozzi *et al* [4] have shown, if neutron backgrounds in DUNE can be mitigated, DUNE could resolve the tension between the KamLAND and solar measurements at high significance. While DUNE will be hard-pressed to observe the MSW transition region directly because of the relatively high threshold for the CC reaction, its high sensitivity to the Day/Night effect would give it a precision measurement of Δm^2_{12}.

For lower-energy solar neutrinos, including the CNO neutrinos, the SNO+ experiment is coming on-line. SNO+ will have 780 tonnes of liquid scintillator that reside within the original SNO acrylic vessel, and with its great depth (2000 m) it will have very low cosmogenic backgrounds. SNO+ has as one of its primary goals a precision measurement of CNO, although this will depend on the level of leaching of Pb and Po isotopes from the vessel. With scintillator, SNO+ will also be able to probe the MSW transition in the ^{8}B solar neutrinos (even after it deploys Te for its $\beta\beta$ search), although statistics may be the limiting factor.

To do better, it is likely that experiments will be needed that can distinguish backgrounds from signal using the directional information available via Cherenkov light, while maintaining the low backgrounds and high energy resolution possible with a scintillation detector. Bonventre and Orebi Gann [5] have shown that with modest angular resolution from Cherenkov light, the CNO neutrinos could be detected distinct from other backgrounds with high significance.

Two future experiments plan on exploiting the ability to observe Cherenkov and scintillation light independently. The Jinping Neutrino Experiment will have 2 ktonnes of LAB liquid scintillator with a very small doping of PPO fluor. The small doping of PPO leads to a very slow emission of the scintillation light (and there is much less of it), thus the Cherenkov light can be seen. The Theia experiment is planned to be much bigger—at least 25 ktonnes of liquid scintillator, but perhaps as much as 100 ktonnes. Theia will do Cherenkov/separation either by using water-based liquid scintillator (which has a smaller number of scintillation photons than standard liquid scintillator) in combination with photosensors with fast timing, slow scintillator, or perhaps using "dichroicons" [6] which sort photons by wavelength. With its large size, Orebi Gann [7] has pointed out that Theia could also be loaded with an isotope like ^{7}Li which has a large CC cross section for solar neutrinos, thus increasing its detection rate and improving the energy response over the very broad ES events typically observed by scintillator detectors.

4.1 Neutrino Interactions

With their important role in both discovering neutral currents, and in understanding the quark structure of nucleons through deep inelastic scattering (DIS), we might expect that understanding neutrino interactions would be complete. Certainly some interactions, like $\nu + e \rightarrow \nu + e$ are completely calculable via Standard Model physics (with the well-known result of $\sigma = \frac{G_F^2 s}{\pi}$). Scattering off of nucleons at low energies (< 10 MeV) is also well understood, with uncertainties as small as $\pm 0.5\%$. The neutrino discovery reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, often referred to as "inverse β decay," (IBD) was an example of this, as was SNO's measurement of CC reactions on deuterons, which is very close to the other IBD reaction, $\nu_e + n \rightarrow e^- + p$ for which the angular distribution of the electron was well-described by calculations.

When the nucleons reside inside nuclei, the problem becomes more complex, but again at energies in which the inelasticity of the reaction is small compared to nuclear transitions, the problem is often tractable. The calculations of the cross section on ^{37}Cl were critical for the discovery of solar neutrinos, for example. Measurements of the cross section on Ga have agreed reasonably well with predictions, at roughly the 10% level. The language used for these calculations is all the language of nuclear physics: transitions to various states are included and in some cases have large impacts.

At the other end of the energy spectrum, where momentum exchanges are large enough that neutrinos scatter off individual quarks, the understanding of the cross sections are again reasonably good. These deep inelastic reactions have a slow energy dependence, and the (entirely calculable) reactions of neutrinos off of quarks gets convolved with the measured distributions of momenta of the quarks inside the nucleon via form factors. While the reaction products can be quite messy, measurements of their inclusive behavior agrees well with predictions.

In between these regimes (100 MeV–10 GeV), however, the picture is less rosy. One complication is that here, multiple processes compete with one another—quasi-elastic reactions (which are the high-energy end of IBD reactions) tail off while resonance production is peaking and DIS begins to rise. Measurements of many of these reactions are decades old and in some cases, do not agree. In addition to the multiple reaction channels, the complexity of the nuclei being used mean that without a detailed understanding of nuclear structure it is hard to predict how often the scattering takes place off of correlated nucleon pairs, or how often multiple nucleons will be emitted. Beyond even this is the fact that the final state products (for example, pions) may re-interact within the nucleus and very different reactions may be indistinguishable. For example, resonance production in which the pion is reabsorbed may be mistaken for the quasielastic reaction $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$.

An obvious solution to dealing with the complexity in this "transition" or "intermediate" regime is to simply avoid it, and for many decades this is what was done. But the discovery of neutrino oscillations, and their relevant mixing parameters, have put this regime into a central place. To study neutrino mixing with accelerators—which provide very precise measurements of θ_{23} and

Δm^2_{23}, and will ultimately measure δ_{CP} and resolve the mass-ordering question—we need the neutrino energy to be above the muon production threshold. Neutrino oscillations in vacuum are dependent upon both a mixing angle, and the mass differences squared, for example for simple two-flavor mixing:

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta sin^2(\frac{1.27\Delta m^2 L}{E_\nu}). \quad (4)$$

The value of Δm^2_{23}, and the requirement that the baseline for these experiments, L, fits inside existing landmasses puts E_ν squarely in the intermediate energy region.

Existing experiments like NOνA and T2K have found their precision to be driven in large part by uncertainties on these intermediate-energy neutrino interactions, and this may also be true for DUNE and Hyper-K, if things remain as they are. A good fraction of the uncertainties associated with the cross sections are mitigated by having "near" detectors that use the same nuclear target as the far detector used to make the oscillation measurements. But the neutrino spectra at the near site are different than that at the far site (just because of the angular dependence and divergence of the beam), and near detectors may be designed to look like the far detector, to reduce other uncertainties, and therefore not be as good at making cross section measurements as a dedicated experiment might be.

To remedy the problem, there are several things that need to happen. The first—and, perhaps, the hardest—is for the international experimental nuclear physics and high energy physics communities to communicate better. As Formaggio and Zeller write in their beautifully comprehensive review on the subject [8], the increase in neutrino quasi-elastic cross sections on nuclear targets was already observed in electron-nucleus scattering measurements when it was "discovered" in neutrino interactions. They say, "In hindsight [the effect] should probably not have come as a suprise...The possible connection between electron and neutrino QE scattering observations has only recently been appreciated."

In addition to more interaction (pardon the pun) between the experimental communities, perhaps new ideas amongst the theoretical communities would be able to provide additional guidance, with an idealistic goal of a full "neutrino interaction generator" that relies less on empirical data. For experiments on argon, like DUNE, this will be particularly important in part because there are so few empirical measurements to begin with.

Of course, more dedicated cross section measurements would be a great benefit. The Minerva experiment at Fermilab has ended, although there will be analyses of their rich data sets for a long time to come. The WAGASCI experiment in Japan is starting up, and it should provide many important measurements. The CAPTAIN experiment is also being discussed for deployment at

Oak Ridge, to probe cross sections in the regime of supernova neutrinos, right at the edge of the intermediate energy regime.

Lastly, more capable near detectors for long baseline experiments will help. T2K is upgrading its near detector suite, and DUNE is planning a very complete near detector complex that will help reduce uncertainties associated with these cross sections. The SBND experiment at Fermilab will also be starting soon, and will observe roughly a million neutrino events in argon before it has ended.

5 Summary

Nuclear physics plays a crucial role in what are really the most compelling neutrino measurements to make: the critical question of whether neutrinos are Majorana particles or not; searches for new physics and new astrophysics in solar neutrinos; and the understanding of neutrino interactions which are a linchpin of the entire future accelerator-based neutrino oscillation program, including the search for leptonic CP violation.

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A global perspective on searches for Electric Dipole Moments

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Abstract. Many experiments are underway in the world to search for a non-zero electric dipole moment (EDM) of a particle with spin 1/2 such as the neutron or the electron. Finding an EDM would reveal new sources of CP violation. EDM measurements are motivated by the high sensitivity to new physics beyond the Standard Model. They are relevant to find the explanation for the the matter-antimatter asymmetry of the Universe. A variety of programs with different systems are being pursued, with free neutrons, diamagnetic atoms, paramagnetic systems, and charged particles in storage rings. This article presents a basic introduction of the subject and attempts to compile the ongoing projects.

1. Introduction

The electric dipole moment (EDM) $\vec{d}$ of a composite system measures the separation of the positive and negative electric charges, it is associated with an energy $-\vec{d}\cdot\vec{E}$ in an external electric field. In fact that interaction term can be taken as the definition of the EDM, even for a non-composite system such as an electron. For any simple system of spin 1/2, the EDM, being a vector operator, must be proportional to the Pauli matrices $\hat{\vec{\sigma}}$ acting on the spin states. The Hamiltonian of a spin 1/2 particle in an electric field is

$$\hat{H} = -d\,\hat{\vec{\sigma}}\cdot\vec{E}, \qquad (1)$$

where d is the permanent electric dipole moment of the particle. Hence, the EDM of a simple particle really quantifies the coupling between the spin and an applied electric field, in the same way that the magnetic dipole moment quantifies the coupling between the spin and a magnetic field.

The coupling (1) results in the dynamics shown in figure 1 (a), for a spin initially perpendicular to the electric field. The spin precesses around the field at an angular frequency given by $\hbar\omega = 2dE$. As shown in figure 1 (b), the mere existence of a non-zero EDM would constitute a violation of time reversal symmetry, because spin precession in an electric field discerns the past and the future.

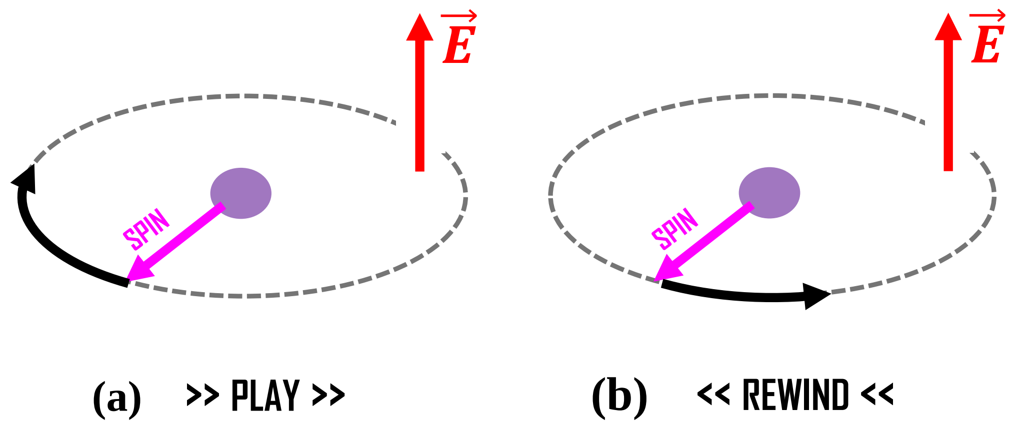

Figure 1. (a) Evolution in an electric field of a particle spin with a non-zero - positive in this case - EDM. (b) Time-reversed version of the evolution (a). The fact that (a) and (b) are different constitutes a violation of time reversal symmetry.

Now, despite decades of experimental efforts, the many measurements of the EDMs of various particles are all compatible with zero. Permanent EDMs, if they exist, are extremely tiny. For example, the current limit on the magnitude of the neutron EDM is [1]

$$|d_n| < 3 \times 10^{-26}\, e\,\mathrm{cm}\ (90\%\ \mathrm{C.L.}). \tag{2}$$

In a large electric field of 10 kV/cm, it would take more - much more? - than 80 days for the spin precession to complete one full turn.

This paper gives a global overview of the quest for a non-zero EDM, an active field of experimental research today. It updates previous overviews on EDM searches [2, 3]. For a more in-depth treatment of the subject, the reader should consult the recent review [4]. In section 2 we will explain the relevance of the EDM searches in particle physics and cosmology. There are many experimental efforts underway worldwide to improve the sensitivity of the EDM searches using various systems. The archetype is the neutron EDM, that we will cover in section 3. In the following sections we will cover the EDM searches with diamagnetic atoms, paramagnetic systems, and finally with charged particles.

2. Relevance of the EDM quest in particle physics and cosmology

From the point of view of relativistic field theory, the EDM of a fermion f corresponds to the following coupling to the electromagnetic field $F_{\mu\nu}$:

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{id}{2} \bar{f}_L \sigma^{\mu\nu} f_R F_{\mu\nu} + h.c. \tag{3}$$

where f_L and f_R are the left and right chirality components of the fermion. In the non-relativistic limit the lagrangian density (3) reduces to the hamiltonian (1). We note

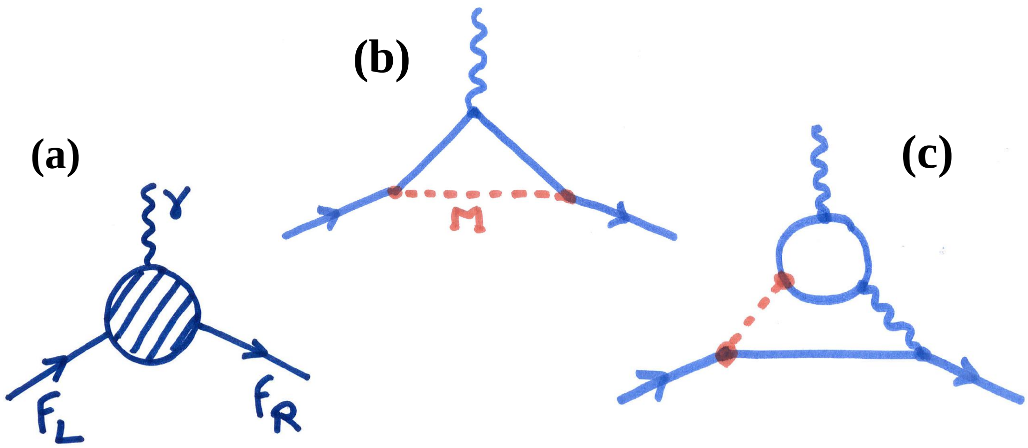

Figure 2. (a) Feynman diagram corresponding to the EDM coupling (3). (b) Example of a one-loop diagram contributing to the fermion EDM. (c) Two-loop Barr-Zee diagram contributing to the fermion EDM.

that the coupling (3) explicitly violates CP symmetry if d is non-zero. It is consistent with the fact that the hamiltonian (1) violates the time reversal symmetry and the CPT theorem which states that T-violation is equivalent to CP-violation in any local relativistic quantum field theory.

The coupling (3), also represented in figure 2 (a), is an effective non-renormalizable interaction which could be generated by the effect of virtual particles. Figure 2 (b) shows a possible diagram involving the virtual exchange of a heavy boson of mass M and with a complex coupling $ge^{i\phi}$ to the fermion. It generates an EDM of $d \approx e\hbar c\, g^2/(4\pi)^2 \sin(\phi)\, m_f/M^2$. This formula can be used to estimate the order of magnitude for the EDM of the first generation fermions – say the d quark ($m_f = 5$ MeV) – induced by a boson at the TeV scale ($M \approx 1$ TeV and $g^2/(4\pi) \approx 10^{-2}$) with maximal CP violation ($\sin(\phi) \approx 1$): we get $d \approx 10^{-25}\, e\,$cm. Therefore generic CP violation above the electroweak scale is positively detectable by EDM experiments.

The non-detection of EDMs reflects the peculiar structure of CP violation in the Standard Model which structurally contains two sources of CP violation: a complex phase in the CKM matrix and the strong phase $\theta_{\rm QCD}$. EDMs induced by the CKM phase are theoretically undetectably small. This is due to the flavour structure of the electroweak theory: only diagrams involving all three generations of quarks in the loops can contribute to the EDM, this results in a big suppression. On the contrary, the strong phase induce in principle large hadronic EDMs. The non-observation of the neutron EDM results in the bound $|\theta_{\rm QCD}| < 10^{-10}$. The fact that the strong phase is measured to be unnaturally small constitutes the *strong CP problem.* It is believed that an unknown dynamics beyond the Standard Model is at play to set this phase to zero.

EDMs are sensitive probes of CP violation effects beyond the Standard Model with practically zero background form the CKM phase. As a concrete example let us consider the search for CP-violating couplings of the Higgs boson h to fermions. The

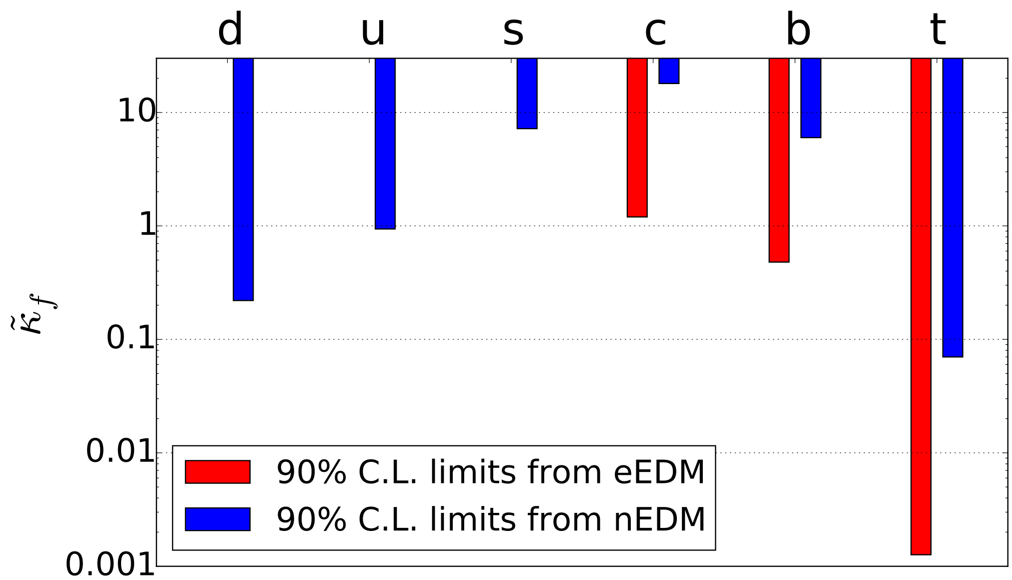

Figure 3. Current limits on the CP-violating couplings of the Higgs boson for the six quark flavours derived from the electron EDM (red bars) and from the neutron EDM (blue bars), adapted from [5].

Higgs couplings are generically parameterized by the following lagrangian

$$\mathcal{L}_h = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f \bar{f}\gamma_5 f h\right), \tag{4}$$

where y_f is the Yukawa coupling of the fermion f, κ_f and $\tilde{\kappa_f}$ are the CP-conserving and CP-violating coupling constants. The Standard Model predicts $\kappa_f = 1$ and $\tilde{\kappa}_f = 0$. This coupling generates EDMs though the two-loops diagram shown in figure 2 (c). The limits on the CP-violating couplings to the quarks derived from the neutron and electron EDM bounds are shown in figure 3. This plot illustrates the complementarity of EDM searches: the electron EDM is more sensitive to $\tilde{\kappa}$ of the heavy quarks while the neutron EDM is more sensitive to $\tilde{\kappa}$ of the light quarks. It also illustrates the great sensitivity of EDM searches: fundamental CP-violating couplings of order unity, relative to CP-conserving couplings, are already excluded except for the s quark. Next generations of EDM experiments will push these limits down by an order of magnitude, or perhaps discover a signal induced by small CP-violation in the Higgs sector.

Let us complete this section by emphasizing the importance of searching for new sources of CP-violation. First, this is a generic feature of models extending the SM, which inevitably come with additional complex (therefore CP-violating) free parameters. More compellingly, cosmology actually demands new CP violation sources to solve the baryon asymmetry puzzle. Several classes of possible baryogenesis models have been invented to explain the generation of the matter-antimatter asymmetry in the early Universe. They almost all have in common to satisfy Sakharov's necessary conditions: (i) process out of thermal equilibrium, (ii) existence of baryon number violation processes, (iii) existence of C and CP violating interactions. An appealing possibility, called

Electroweak baryogenesis, poses that baryogenesis occurred at the electroweak phase transition epoch of the Universe, at a temperature of about 100 GeV. See [6] for a recent discussion on the subject. For baryogenesis to work, new CP-violating interactions must have been active at this temperature, therefore the mass of the new particles could not be much heavier than 1 TeV and and the CP-violating interaction they mediate should be sufficiently strong. The models therefore also predict sizable EDMs and the future EDM experiments will either discover a nonzero EDM or exclude most of electroweak baryogenesis models.

3. Search for the neutron EDM

The history of EDM searches started with the neutron in the 1950's. The basic idea is to use polarized neutrons and measure precisely the spin precession frequency f in parallel or antiparallel magnetic and electric fields:

$$f = \frac{\mu}{\pi\hbar} B_0 \pm \frac{d}{\pi\hbar} E. \tag{5}$$

The EDM term can be separated from the much larger magnetic term by taking the difference of the frequency measured in parallel and antiparallel configurations. As we discussed in the introduction, the EDM term is very small ($dE/\pi\hbar \approx 10^{-7}$ Hz for $d = 10^{-26}\, e\,\mathrm{cm}$ and $E = 15\,\mathrm{kV/cm}$) compared to the magnetic term (typically, $f = 29\,\mathrm{Hz}$ for $B_0 = 1\,\mu\mathrm{T}$). To detect such a minuscule coupling, one needs (i) a long interaction time of the neutrons with the fields, (ii) a high flux of neutrons and (iii) a precise control of the magnetic field. The first experiment by Smith, Purcell and Ramsey [7] used a beam of thermal neutrons passing in the electric field during $T \approx 1$ ms. The precession time could be greatly increased by using *ultracold neutrons* (UCNs). These are neutrons with a kinetic energy smaller than the neutron optical potential of solid materials, typically 100 neV. These neutrons can therefore be stored in material traps because they undergo total reflection upon collision with the walls of the trap. In the best previous measurement [1] performed at ILL in the period 1998-2002, UCNs were stored in a chamber permeated by a weak magnetic field and a strong electric field during $T \approx 100$ s. Although the systematic error is also a big concern, this measurement was limited by the statistical error and thus by the intensity of the ILL/PF2 UCN source. New higher intensity UCN sources are now coming online at several major neutron factories worldwide, which are exploited by several nEDM projects. In particular, the nEDM experiment has collected data [8] in 2015-2016 at the PSI UCN source, which will result in a slightly improved measurement of the neutron EDM (the analysis is still ongoing at the time of writing). Other ongoing nEDM projects [12, 13, 14, 15, 16, 17] are listed in table 1, they are all at a different stage of readiness and they aim at an improvement in sensitivity by a factor 10 to 100 compared to the previous measurement [1]. More details on nEDM searches can be found in the recent reviews [9, 10].

Table 1. List of active ongoing projects [11] searching for the EDM of the neutron, diamagnetic atoms (Hg, Xe, Ra), paramagnetic systems and charged particles.

project	location	concept	references
nEDM@SNS	Oak Ridge spallation source	UCN in superfluid helium	[12]
n2EDM	PSI spallation source	UCN double chamber	[13]
nEDM@LANL	Los Alamos spallation source	UCN double chamber	[14]
panEDM	ILL reactor Grenoble	UCN double chamber	
TUCAN	TRIUMF spallation source	UCN double chamber	[15]
PNPI nEDM	ILL - PNPI	UCN double chamber	[16]
beam nEDM	ESS spallation source	pulsed cold neutron beam	[17]
Hg EDM	Seattle	vapor cells mercury-199	[18]
quMercury	Bonn	laser cooled mercury-199	
MIXed	Jülich - Heidelberg	xenon-129 + helium-3	[19]
HeXeEDM	Berlin	xenon-129 + helium-3	[20]
Xe EDM	Riken	xenon-129 + xenon-131	[21]
Ra EDM	Argonne	laser-cooled radium-225	[22]
Cs,Ru EDM	Penn State	trapped cold alkali	[24]
Fr EDM	CYRIC, Riken	laser-cooled francium	
EDM^3	Toronto	BaF within a rare gas matrix	[25]
NL-eEDM	Nikhef	BaF cold beam	[26]
JILA EDM	Boulder	trapped molecular ions HfF^+ ThF^+	[27]
ACME	Yale	cryogenic ThO beam	[28]
eEDM	London	slow YbF beam	[29]
CPEDM		proton or deuteron storage ring	
muEDM	PSI	compact muon ring, frozen spin	[30]
μ g-2/EDM	JPARC	compact muon ring	[31]
μ g-2	Fermilab	magic momentum muon ring	[32]

4. Search for the EDM of diamagnetic atoms

Diamagnetic atoms are atoms with no net electronic spin. Due to this property, very high precision can be obtained for the EDM of diamagnetic atoms with nuclear spin 1/2, in particular mercury-199, xenon-129 and radium-225.

In the case of mercury-199, super-precise monitoring of the spin precession can be achieved by making use of atom-light interaction. The current best limit is [18]:

$$|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30}\, e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}) \quad (6)$$

In the case of xenon-129, the measurement profit from the very long coherence time (many hours) of the spin precession. The current best limit is [19]:

$$|d_{\mathrm{Xe}}| < 1.5 \times 10^{-27}\, e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}) \quad (7)$$

It is important to note that these limits apply to the atomic EDM and not the nuclear EDM. As stated by Schiff's theorem, a nuclear EDM is shielded by the electrons and does not generate an atomic EDM. Instead, atomic EDMs could possibly be generated by two sources: (i) T-violating electron-nucleon interactions, or (ii) a nonzero nuclear Schiff moment. The Schiff moment is a T-odd nuclear deformation which generates an electric field inside the nucleus along the spin. That electric field is pulling the electrons in s orbitals therefore generating an atomic EDM. The Schiff moment itself could be generated by either T-violating nucleon-nucleon interactions or by a nucleon EDM. Overall the effect is larger in heavy nuclei, hence the experimental focus on mercury-199 and xenon-129. At the end, the shielding effects are compensated by the better absolute sensitivity of experiments with diamagnetic atoms, as compared to the neutron. All diamagnetic systems (neutron, mercury and xenon) have comparable and complementary sensitivity to fundamental sources of CP-violation [4]. Also, Schiff moments are enhanced in octupole-deformed nuclei. This has motivated recently the search for EDMs of radioactive nuclei such as radium-225. The current best limit is [22]:

$$|d_{\rm Ra}| < 1.4 \times 10^{-23}\, e\,{\rm cm}\ (95\%\ {\rm C.L.}). \tag{8}$$

The search for EDMs of diamagnetic atoms is very active today, with prospects to improve the sensitivity by a factor 100 in all three systems. The ongoing projects [18, 19, 20, 21, 22] are listed in table 1.

5. EDM searches with paramagnetic atoms and polar molecules

Paramagnetic systems, i.e. atoms or molecules with an unpaired electron, can be sensitive to T-violating electron-nucleon interactions and to the electron EDM. The most sensitive probes are atoms with large Z, in particular cesium of radioactive francium, and heavy polar molecules like BaF, ThO, YbF, or even molecular ions HfF^+, ThF^+. We refer to the recent review [23] for more details about the search for EDMs with atoms and molecules. The current best limit on the electron comes from the ACME experiment with ThO molecule [28]:

$$|d_e| < 1.1 \times 10^{-29}\, e\,{\rm cm}\ (90\%\ {\rm C.L.}). \tag{9}$$

There are several projects [24, 25, 26, 27, 28, 29], listed in table 1, aiming at improving the sensitivity on the electron EDM by a factor of 100 or more.

6. Search for the EDM of charged particles in a storage ring

Polarized charged particles, in particular protons, deuterons or muons, can be confined in circular storage rings with either a radial electric field, or a vertical magnetic field, or a combination of both. It is apparently not a good situation to measure an EDM since the electric and magnetic fields cannot be made parallel or antiparallel and the classic EDM search strategy does not work for charged particles. The situation is in fact more complicated, because contrary to classic EDM searches with particles practically at rest, the relativistic motional fields $\vec{E} \times \vec{v}$ and $\vec{B} \times \vec{v}$ are not small for charged particles in a storage ring. In the frame rotating with the cyclotron motion, the precession vector of the spin is given by the BMT equation:

$$\vec{\omega} = \frac{q}{m} \left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2} \right) \vec{v} \times \vec{E} \right] + 2d \left[\vec{v} \times \vec{B} + \vec{E} \right], \tag{10}$$

where q is the charge of the particle, m its mass and $a = (g-2)/2$ is the magnetic anomaly. The first term is due to the magnetic dipole. The second term is due to the electric dipole, it makes the spin move out of the plane of the ring. The EDM signal corresponds to a build up of the vertical component of the spin. In some cases it is possible to enhance the sensitivity of the search by setting the first magnetic term to zero, a technique called the *frozen spin*, by an appropriate choice of the parameters B, E, v. Ongoing projects pursuing the developments of EDM measurements with charged particles are listed in table 1.

7. Conclusion

The search for a non-zero fundamental electric dipole moment is an interdisciplinary field. The motivation comes from particle physics and cosmology. A broad range of experimental techniques are developed ranging from the large scale neutron facilities to advanced atomic physics. We have presented an overview of the theoretical motivations and the experimental programs to search for the EDMs with free neutrons, diamagnetic atoms, paramagnetic systems and charged particles. We must admit we have omitted the proposals to measure EDMs of heavy unstable particles (lepton τ, hyperons and charmed baryons) at particle colliders, due to the temporary incompetence of the author on this connected field. In figure 4 we show the world map of the ongoing EDM projects, with an estimate of the number of scientists involved. The diversity of the experiments promise exciting prospects for the future, and maybe a discovery of fundamental importance.

Acknowledgments

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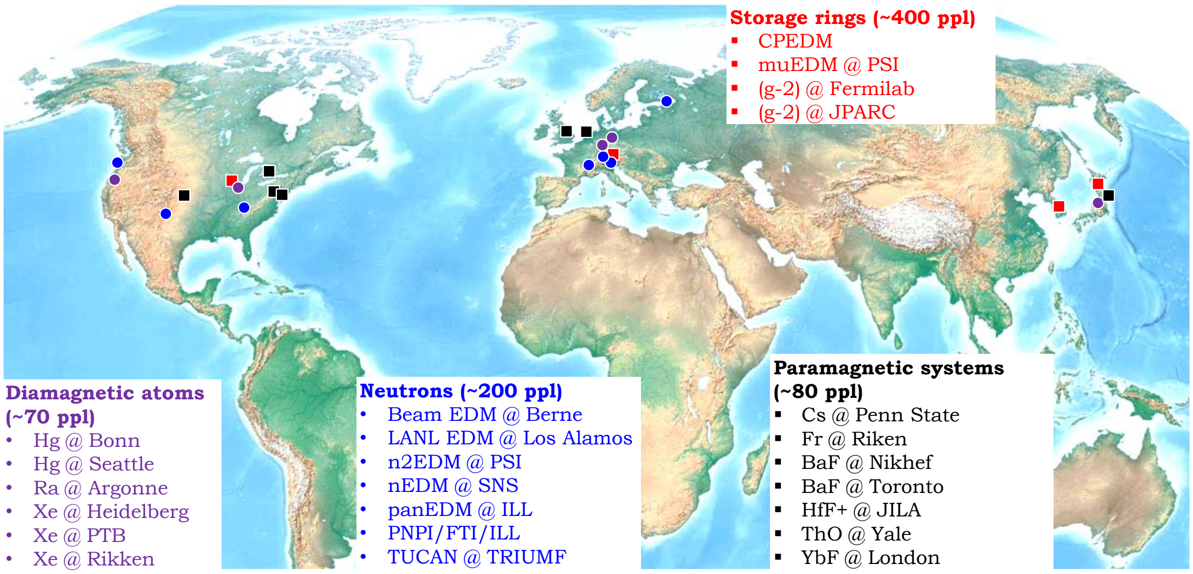

Figure 4. The world view on EDM searches, with an estimate of the number of physicists involved, adapted from [11].

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Searching for physics beyond the Standard Model with hadronic and nuclear probes

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Abstract. In this talk I provide a theoretical perspective on low-energy searches for physics beyond the Standard Model, involving hadrons and nuclei. After a short introduction on the so-called energy and precision frontier searches, I focus on the latter, describing the theoretical framework to interpret such searches and a few selected examples. These include neutrinoless double beta decay, permanent electric dipole moments, and precision beta decay measurements.

1. The quest for new physics: Energy and Precision / Intensity Frontiers

The Standard Model (SM) of strong and electroweak interactions, while markably successful, suffers from a number of shortcomings. When combined with the standard cosmological model, the SM fails to explain the existence of the observed bayron asymmetry, dark matter, and dark energy. Moreover, with its minimal field content, the SM does not account for neutrino masses. The SM also leaves unanswered a number of more theory-driven questions such as the large hierarchy between the weak and the Planck scales, the origin of families and flavor, the possibility of unification of forces at high energy. The solution to both the observational and theoretical puzzles likely requires new degrees of freedom and new dynamics, which motivates the search for new physics.

In broad brush one can expect that new physics has escaped detection so far because the new particles are either very heavy or light and weakly coupled. Traditionally, there are two routes to search for new physics in laboratory experiments: one is to push the energy of particle accelerators so as to try to directly produce new particles – this is known as the "energy frontier". The other route is to perform very precise and sensitive measurements in low-invariant mass systems, which allows us to indirectly access the virtual exchange of heavy degrees of freedom or directly excite light and weakly coupled particles – this is known as the "precision frontier". This second route requires using ultra-sensitive detectors and / or powerful particle accelerators to generate large fluxes of particles such as neutrinos, muons, mesons, neutrons, etc. – hence sometime the name "intensity frontier". Both energy and precision / intensity frontiers are needed to reconstruct structure, symmetries, and parameters of the underlying new dynamics governed by $\mathcal{L}_{\rm BSM}$ [1, 2, 3]. For example, while high-energy colliders are the most powerful probe of the electroweak symmetry breaking mechanism, typically precision frontier experiments provide the strongest probes of lepton (L) and baryon (B) number violation, CP violation, flavor violation in the quark and lepton sectors, neutrino properties, and dark sectors. Nuclear Science Fundamental Symmetry (NSFS) experiments play a prominent role at the precision frontier, as often the best laboratories to probe symmetry violations are provided by hadronic and nuclear systems.

To establish the context in which NSFS experiments operate, it is essential to know the status of the complementary energy frontier searches as well as intensity frontier searches in the flavor sector. The premier facility for energy frontier searches is the Large Hadron Collider (LHC) that has recently completed Run 2. So far the LHC has delivered a major discovery, the Higgs boson at mass of 125 GeV [4, 5], so far is compatible with the SM Higgs [6]. On the other hand, searches for new particles have yielded negative results, pushing the simplest scenarios of new physics tp the TeV scale or above, or forcing them to have a compressed spectrum [6]. The high-luminosity and high-energy upgrades of the LHC [7] are the immediate next step in the pursuit of new physics at high energy, in the next decade. Last but not least, within the landscape of non-nuclear searches for new physics a prominent role is played by intensity frontier searches focusing on meson decays, such as K meson at NA62 (CERN) KOTO (J-PARC) [8], and B meson decays at LHCb [9] and Belle-II [10]. Some interesting anomalies have emerged in B decays, which have triggered much attention in the literature (see for example Ref. [11]). New physics scenarios explaining the lepton flavor universality anomalies in B decays typically do not predict correspondingly large signals in nuclear and hadronic probes involving first-generation quarks [11].

2. Precision / Intensity frontier searches: a theory overview

Within the precision frontier one can identify three classes of probes, within which essentially all current experimental efforts in Nuclear Science fall:

- Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM. These include proton decay, neutron-antineutron oscillations, neutrinoless double beta decay ($0\nu\beta\beta$), permanent electric dipole moments (EDMs), $\mu \to e$ conversion in nuclei, quark flavor violation. These probes are primarily sensitive to ultraviolet (UV) new physics, with some notable exceptions ($0\nu\beta\beta$ and sterile neutrinos).
- Precision measurements of SM-allowed processes, such as β-decays (neutron, nuclei), parity-violating electron scattering, muon properties (lifetime, muon anomalous magnetic moment). These measurements (note that this is not an

exhaustive list) probe indirectly both UV new physics and light new physics in the infrared (IR).

- Searches for (and characterization of) light weakly coupled particles. These include active neutrinos, sterile neutrinos, dark photon, dark Higgs, axion, etc.

To efficiently interpret the impact of precision frontier searches, general theoretical frameworks have been developed for both UV and IR new physics, encompassing many underlying models. For IR new physics involving a dark sector, one can classify all possible connections between dark sector and SM in terms of so-called portals, operators that are neutral under the SM. The lowest dimension portals lead to possibly complete models (so called vector, neutrino, and Higgs portals). For a discussion of these I refer to the contribution by S. Reddy and Ref. [12] and references therein.

For heavy (UV) new physics the general framework is based on the observation that heavy new particles affect low-energy physics through local operators suppressed by inverse powers of heavy scale. So UV new physics leaves its imprint at low-energy via a series of higher dimensional operators suppressed by the scale of new physics [13, 14], generically indicated here as Λ:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \, O_n^{(d)} \tag{1}$$

Operators up do dimension six have been classified in Refs. [15, 16], and for certain observables one needs to go to even higher dimension. The scale Λ represents generically the mass of the lowest-lying new particles appearing in the underlying new theory. The Wilson Coefficients $c_n^{(d)}$ encode information about the underlying model (couplings, ratio of masses, etc). If the underlying model is known, the Wilson coefficients can be calculated in terms of the model parameters. The above effective Lagrangian describes the low-energy limit of any UV extension of the SM, and defines the so-called SM Effective Field Theory (EFT). This EFT allows one to connect low-energy probes of new physics to high energy probes. It is still written in terms of quarks and gluons, so proceeding to lower energies, to connect to hadronic / nuclear observables, one has to switch to a description in terms of mesons and nucleons, and eventually nuclei, using tools such as chiral EFT, lattice QCD, dispersion relations, quantum many body methods. I emphasize that it is only through such a chain of EFTs that one can connect hadronic and nuclear observables to the underlying BSM parameters (masses, couplings, CP-violating phases, etc) that may shed light on the open problems of the SM.

With this in mind, precision frontier experiments enrich the overarching search for new physics by providing [17]: (i) Discovery potential, (i.e. new ways to look for cracks in the SM); (ii) Diagnosing power (e.g. nultiple EDM searches may shed light on the underlying sources of CP-violation); (iii) Connection to big open questions e.g. unique sensitivity to symmetry breaking required by Sakharov conditions for baryogenesis (B, L, CP), sensitivity to models explaining the origin of dark matter. Nuclear Science Fundamental Symmetries experiments cluster around open questions often probing dynamics otherwise inaccessible. Figure 1 illustrates the interconnections between the

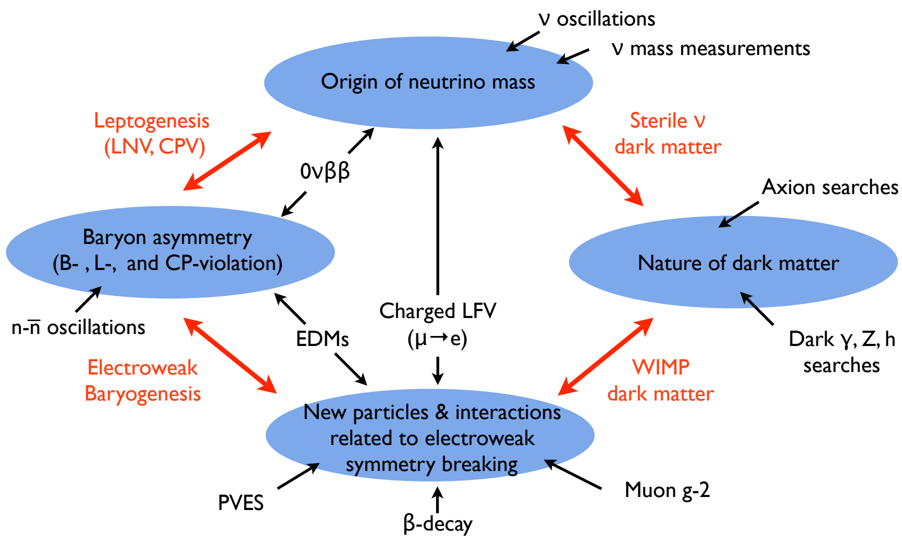

Figure 1. Interconnections between the big open questions and the Nuclear Science "fundamental symmetries" experiments.

big open questions [1, 3] and the Nuclear Science experiments. Next I will discuss two examples of Symmetry violation tests (neutrinoless double beta decay and EDMs) and one example of precision measurements (β decays), highlighting the discovery potential, diagnosing power and the status of theoretical hadronic / nuclear calculations.

3. Rare / Forbidden processes

3.1. Neutrinoless double beta decay and lepton number violation (LNV)

Neutrinoless double beta decay is a rare nuclear process, observable only in certain even-even nuclei for which single beta decay is energetically forbidden, in which two neutrons convert into two protons with emission of two electrons and no neutrinos, thus changing the number of leptons by two units. Since lepton number is conserved in the SM (more precisely at the quantum level $B - L$), observation of $0\nu\beta\beta$ would be direct evidence of new physics, with far reaching implications: it would demonstrate that neutrinos are Majorana fermions [18], shed light on the mechanism of neutrino mass generation [19, 20, 21], and probe lepton number violation (LNV), a key ingredient needed to generate the matter-antimatter asymmetry in the universe via "leptogenesis" [22]. Due to this outstanding scientific motivation, a vigorous worldwide experimental program exists, geared towards the construction of a ton-scale experiment (with half-life reach in the 10^{27-28} years) range. The experimental aspects are discussed in the contribution by J. Klein.

Ton-scale $0\nu\beta\beta$ searches will probe at unprecedented levels LNV from a variety of mechanisms. For example, the standard seesaw originates at very high scale, through the exchange of super-heavy R-hadned neutrinos which leave behind at low-energy a

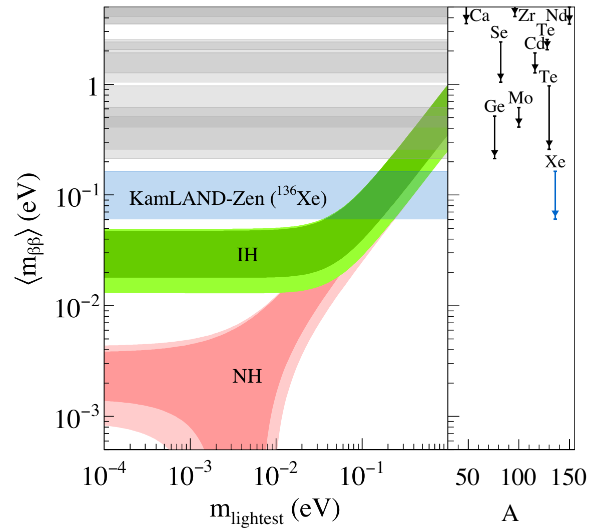

Figure 2. $|m_{\beta\beta}|$ versus lightest neutrino mass for both normal (red band) and inverter spectrum (green band). Plot taken from A. Gando *et al.* [KamLAND-Zen Collaboration], Phys. Rev. Lett. **117**, no. 8, 082503 (2016) [23].

single dimension-5 operator [13] in Eq. (1), which below the electroweak scale becomes a Majorana mass for light neutrinos. Alternatively LNV could originate at intermediate scale, close to the TeV (and hence accessible at the LHC), as for example the Left-Right Symmetric Model. In this case the exchange of heavy particles leaves behind different operators of higher dimension (7, 9, 11, ...) in Eq. (1) that can compete with light-neutrino exchange provided the the scale is not too high and the relevant Yukawa couplings are sufficiently small. Quite importantly, these TeV scale mechanisms lead to different transition operators at the nuclear scale. Finally, LNV could be lurking at very low-scale, through mass terms of light sterile neutrinos. I will next discuss the various scenarios, starting with the high-scale seesaw [19, 20, 21].

3.1.1. High scale seesaw: In this case $0\nu\beta\beta$ is a direct probe of ν mass matrix. The decay rate scales as $\Gamma \propto |M_{0\nu}|^2 m_{\beta\beta}^2$ where $M_{0\nu}$ is the nuclear matrix element and $m_{\beta\beta} = \sum_i U_{ei}^2 m_i$ is the "*ee*" component of the Majorana mass in the flavor basis. From oscillation experiments a lot is known on $m_{\beta\beta}$, but not everything [6]. The unknowns are two Majorana phases, the ordering of the spectrum ($m_{\rm lightest} = m_1$ or $m_{\rm lightest} = m_3$) and the value of $m_{\rm lightest}$. This implies that in the $m_{\beta\beta}$ vs $m_{\rm lightest}$ plane one has two bands, whose width is due to the unknown Majorana phases. The state of affairs is summarized in Fig. 2, including the experimental constraint on $m_{\beta\beta}$ from Ref. [23]. Experimental sensitivities appear as horizontal bands rather than lines, due to the current uncertainties in the nuclear matrix elements $M_{0\nu}$, which can vary by a factor of 3 depending on which model is adopted in the calculation [24]). Next generation experiments aim to cover the entire "inverted hierarchy" (green) band in $m_{\beta\beta}$, assuming the smallest available matrix elements. A discovery will be possible if the case of inverted spectrum or $m_{\rm lightest} > 50$ meV, irrespective of the ordering.

Note that the interplay of $0\nu\beta\beta$ with other neutrino mass probes, namely $m_\beta \equiv (\sum_i |U_{ei}|^2 m_i^2)^{1/2}$ from tritium beta decay and $\Sigma \equiv \sum_i m_i$ from cosmology can test high-scale seesaw model and possibly unravel new sources of LNV or physics beyond ΛCDM + m_ν in cosmology. For example, the next generation m_β experiments [25, 26] and cosmology [27] might rule out inverted spectrum $m_{\rm lightest} > 50$ meV. In that case the observation of $0\nu\beta\beta$ in the next generation experiments would indicate new LNV sources, beyond $m_{\beta\beta}$. Moreover, cosmological observations may soon be able to detect a signal for Σ, which would translate in a definite range for $m_{\beta\beta}$, that can be probed in next generation searches.

The above discussion assumes that we know matrix elements with sufficient precision, which is not currently the case [24]. The theory community has recently undertaken several steps towards achieving controllable uncertainties in matrix elements. These include (i) the use of chiral EFT as guiding principle [28]; (ii) the use of first-principles methods in light nuclei [29, 30] to benchmark other methods that can be extended to heavy nuclei of experimental interest; (iii) preliminary ab initio nuclear structure calculations with QCD-rooted potentials for nuclei of interest [31]. I have been involved in task (i) and will briefly summarize the main insight from a chiral EFT analysis of the problem. The EFT analysis shows that to leading order in Q/Λ_χ where $Q \sim m_\pi \sim k_F$, the $nn \to pp$ transition operator for nuclear structure calculations should include not only the usual long-range neutrino exchange but also a short-range contribution [28, 32], completely expected in QCD (non-factorizable terms in the T-ordered product of two weak currents). This is illustrated in Fig. 3. The presence of the contact interaction is required by renormalization of the $nn \to ppee$ amplitude (with nucleons in the $^1S_0$ channel). Removal of UV divergences and regulator dependence requires introducing a short range coupling g_ν. A renormalization group analysis shows that the coupling flows to values $\sim 1/k_F^2$, same order as the tree-level neutrino exchange. This coupling encodes exchange of neutrinos with virtualities much greater than the nuclear scale. One can expect significant impact of the (currently unknown) g_ν on $m_{\beta\beta}$ phenomenology (this has been shown explicitly in light nuclei [33]). Several approaches to estimate g_ν exist. They are based on (i) chiral and isospin symmetry relating g_ν to $I = 2$ electromagnetic couplings [28, 32, 33]; (ii) lattice QCD calculations [34, 35, 36]. Given the potentially large impact on the phenomenology, work is underway on several fronts to estimate the finite part of g_ν.

3.1.2. LNV from multi-TeV scale dynamics: TeV sources of LNV (such as a heavy right-handed neutrino) may lead to sizable contributions to $0\nu\beta\beta$ not directly related to the exchange of light neutrinos. LHC can compete with $0\nu\beta\beta$ to constrain the parameter space of certain models, see for example Refs. [37, 38]. Note that the new contributions from TeV scale LNV can interfere with $m_{\beta\beta}$ or add incoherently, significantly affecting the interpretation of experimental results ‡.

‡ A pattern of destructive interference arises also in the presence of a fourth (sterile) neutrino with mass in the eV range [39].

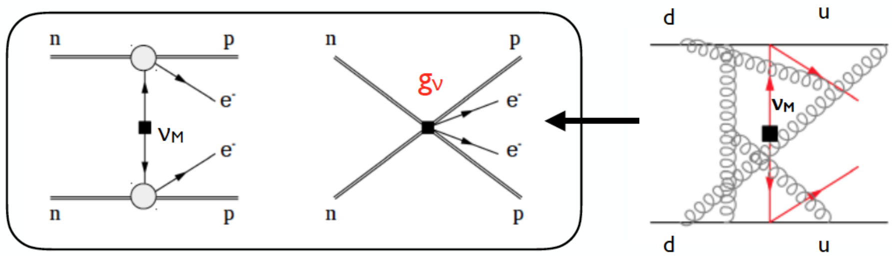

Figure 3. Graphical representation of leading order contributions to the $nn \to pp$ transition operator. The short-range nucleon-level operator originates from the QCD diagram to the right, involving the exchange of Majorana neutrinos and gluons.

The effects of TeV-scale LNV show up at low energy as operators of dimension seven, nine, and higher. Attempts to systematically characterize $0\nu\beta\beta$ rates within an EFT for LNV go back to Refs. [40, 41]. Use of chiral EFT was pioneered in Ref. [42] and a general analysis with correct chiral EFT power counting was performed in Refs. [43, 44]. A lattice QCD program to compute the relevant hadronic matrix elements has been initiated [45].

In summary, ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27-28}$ yr) have significant discovery potential, regardless of the properties of neutrino mass extracted from experiment (e.g. even if we are in the normal ordered spectrum). This is ultimately because we do not know the scale Λ associated with LNV. In combination with oscillation experiments., direct mass measurements, cosmology and LHC, we can probe the underlying sources of LNV. Exciting prospects to improve theory uncertainties exist, thanks to synergy of EFT, lattice QCD, and nuclear structure.

3.2. Permanent Electric Dipole Moments

EDMs provide a deep probe of new physics because they are essentially free of SM background (from CKM CP-violation) and they probe new sources of CP-violation much needed in electroweak baryogenesis mechanisms. For a detailed discussion of EDMs, see contribution by G. Pignol and the excellent reviews [46, 47] (and references therein). Here I simply reiterate that EDMs have broad sensitivity to new physics, which makes them more relevant than ever in the LHC era. EDMs provide the strongest constraints of CP-violating couplings of the Higgs boson to fermions and gauge bosons [48, 49, 50, 51, 52, 53, 54, 55]. Moreover, EDMs are one of few observables probing PeV scale SUSY [56, 57, 58]. And finally, EDMs probe dark sectors, ALPs (Axion Like Particles), axion Dark Matter [59, 60, 61, 62]. The theory interpretation framework for hadronic and nuclear EDMs is complex and it has been worked out in the context of chiral EFT [63, 64]. Lattice QCD is making steady progress towards the calculation of the relevant nucleon matrix elements (for recent results see [65, 66, 67] and references therein).

4. Precision Measurements

β decays and parity-violating electron scattering have played a central role in establishing the Standard Model [68, 69, 70]. Today, with fractional precision approaching the 0.1% level (together with the muon anomalous magnetic moment at the ppm level!) they probe quantum effects in the Standard Model at unprecedented levels and have "broad band" sensitivity to new physics. Due to space constraints, I discuss here only one example – beta decays as a precision tool to look for new physics.

4.1. Neutron and nuclear beta decays

In the SM the charged current (CC) weak processes are mediated by tree-level W exchange, and are characterized by (i) the $V-A$ structure of the leptonic and hadronic currents, with other types of couplings—$V+A, S, P, T$—arising at higher order in radiative corrections or in recoil momentum; (ii) universal gauge coupling, up to a unitary mixing of quarks in their coupling with the W boson, encoded in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. Precision beta-decay measurements probe the existence of non-SM interactions, which effectively induce violations of the universality relations and/or novel non-$(V-A)$ structures. At a precision of 0.1% or better, they provide powerful constraints and diagnostics on virtually any TeV-scale SM extension, since new effects originating at the scale $\Lambda_{\rm BSM}$ produce corrections to beta decays of size $\mathcal{O}((v/\Lambda_{\rm BSM})^2)$, where $v=(2\sqrt{2}G_F)^{-1/2}\approx 174$ GeV.

The phenomenological analysis of beta decays is greatly simplified by the observation that the leading BSM effects arising from *any* model are encoded by dimension-six operators in Eq. (1), which at low-energy reduce to ten non-standard couplings $\epsilon_i, \tilde{\epsilon}_j$

$$\mathcal{L}_{CC}^{BSM} = -\sqrt{2}\, G_F\, V_{ud} \sum_{i=L,R,S,P,T} \left\{ \epsilon_i\, \bar{e}\, \Gamma_i^e\, \nu_{eL} \cdot \bar{u}\, \Gamma_i^q\, d + \tilde{\epsilon}_i\, \bar{e}\, \tilde{\Gamma}_i^e\, \nu_{eR} \cdot \bar{u}\, \Gamma_i^q\, d \right\}, \quad (2)$$

where $\nu_{L,R} = 1/2(1\mp\gamma_5)\nu$ and $\Gamma_L^{q,e} = \Gamma_R^e = \gamma^\mu(1-\gamma_5)$, $\Gamma_R^q = \tilde{\Gamma}_{L,R}^e = \gamma^\mu(1+\gamma_5)$, $\Gamma_S^{q,e}=1$, $\Gamma_P^{q,e}=\gamma_5$ $\Gamma_T^{q,e}=\sqrt{2}\sigma_{\mu\nu}$, $\tilde{\Gamma}_{S,P,T}^e = \Gamma_{S,P,T}^e$. The non-standard couplings $\epsilon_\alpha, \tilde{\epsilon}_\beta$ are dimensionless, and the ϵ_α's affect beta decay observables linearly (through interference with the SM amplitude), while the $\tilde{\epsilon}_\beta$'s enter only quadratically (the interference is proportional to m_ν/E_ν). The non-standard couplings are probed by a variety of observables, ranging from total decay rates to decay spectra and decay correlations. Theoretical and experimental status has been recently reviewed in Ref. [71].

Perhaps the most important precision test in CC interactions involves the unitarity of the Cabibbo-Kobayashi-Maskawa matrix, quantified by

$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1\ . \quad (3)$$

Currently, the extraction of V_{ud} is dominated by nuclear $0^+\to 0^+$ decays [72], while V_{us} is dominated by $\Gamma(K\to\pi e\nu)$ and $\Gamma(K\to\mu\nu)/\Gamma(\pi\to\mu\nu)$ (see [73] and references therein). Up until very recently one had $\Delta_{\rm CKM} = -(5\pm5)\times10^{-4}$, providing a quite impressive check of the SM. However, a recent dispersive calculation of the radiative corrections [74, 75] has revealed a discrepancy with the previous analysis [76], finding a larger effect and outside of the previously quoted error bar. Using the radiative corrections of Ref. [74] one finds a 4.5 σ (3.5 σ) deviation from unitarity when using V_{us} from $K \to \pi e \nu$ ($K \to \mu\nu$). The discrepancy reduces to 3 σ (2 σ) if one uses the radiative corrections re-analysis from Ref. [77] Ultimately, to have a full assessments of the uncertainty on the radiative corrections, one will need either data to be used in the dispersive representatio [75] or a lattice QCD calculation using the technology developed for meson decays [78] or alternative methods [79]. Finally, note that the neutron will become competitive in the extraction of V_{ud}, provided the precision in the lifetime reaches $\delta\tau_n \sim 0.35$ s ($\delta\tau_n/\tau_n \sim 0.04$ %) and the precision in the decay correlations achieves $\delta A/A \sim \delta a/a \sim 0.14$ %.

Finally, assuming that the BSM physics generating new effects in CC interactions arises at very high scale, one can adopt the EFT formalism to analyze collider data and actually make an "apples-to-apples" comparison of sensitivities between β decays and the LHC [80, 81, 82]. Such a study has been performed for both scalar and tensor couplings ($\epsilon_{S,T}$) and left ($V - A$) and right ($V + A$) vertex corrections ($\epsilon_{L,R}$), and I will briefly highlight the latter. Due to $SU(2)$ gauge invariance, vertex corrections operators in Eq. (1) inducing $\epsilon_{L,R}$ involve the Higgs field and can be probed in associated production of Higgs and W at the LHC [82]. Similarly, ϵ_L also corrects Z-quark-quark vertex and is constrained by Z-pole measurements [83]. Finally, ϵ_R can be independently constrained because experiments always measures the combination $\lambda = g_A(1-2\epsilon_R)$ and lattice QCD can now compute g_A at the percent level [84]. As Fig. 4 shows, turning on only the vertex-correction couplings $\epsilon_{L,R}$, β decays are quite competitive with collider (probing effective scales $\Lambda_{L,R} > 10$ TeV). Going beyond a 2-coupling analysis relaxes some of these constraints (but not the one on ϵ_R from g_A). Even in the case of multiple couplings, β decays provide independent *very competitive* constraints in a global analysis of the SM-EFT effective couplings.

5. Conclusions

Energy and Precision frontiers are exploring uncharted territory in our search for BSM physics. Vibrant Nuclear Science portfolio probes BSM dynamics related to open questions about our universe. Current and planned nuclear science experiments provide competitive probes of dark sectors and new physics up to $\Lambda \gg$ TeV. It is a "win-win" situation: Should new physics appear at the LHC, Nuclear Science probes will play a key role in understanding the symmetries of BSM dynamics and disentangle models. Should new physics not appear at the LHC, the precision frontier will be for a while the only laboratory tool to explore new physics.

6. References

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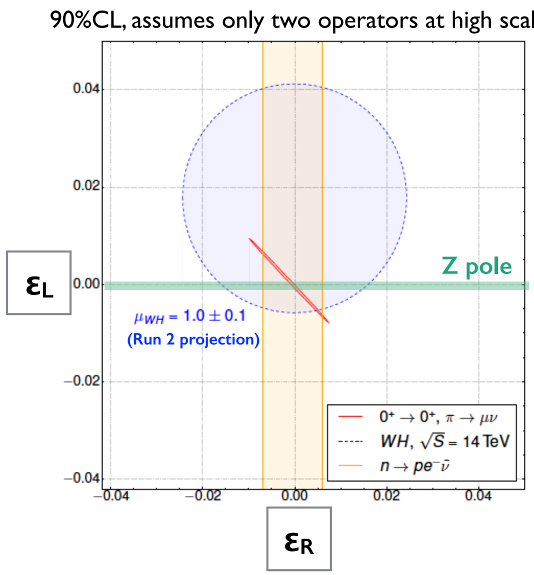

Figure 4. Constraints on the ϵ_R-ϵ_L plane from both β decays and collider observables.

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