Fundamental symmetries, neutrinos, neutrons, and astrophysics: a White Paper on progress and prospects

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I. EXECUTIVE SUMMARY

This White Paper summarizes the recent accomplishments and major opportunities for the study of fundamental symmetries, neutrinos, neutrons in nuclear physics and related areas of nuclear astrophysics. Community input for this White Paper was obtained at a DNP-sponsored Town Meeting held in Chicago (September, 2014) and through solicitation of community "position papers". Through this process, the community has addressed unprecedented opportunities for nuclear science in developing the new Standard Model of fundamental interactions, building on significant advances obtained since the 2007 Long Range Plan. These opportunities bear on three of the eleven questions identified in the 2007 Long Range Plan as characterizing the mission of the field:

- What are the masses of neutrinos and how have they shaped the evolution of the universe?
- Why is there more matter than antimatter in the present universe?
- What are the unseen forces that disappeared from view as the universe expanded and cooled?

In addition, the opportunities with neutrinos and fundamental symmetries in nuclear physics address at least three additional questions for the field that pertain to nuclear astrophysics and QCD:

- What is the internal landscape of the proton ?
- What causes stars to explode ?
- What is the origin of the heavy elements from iron to uranium ?

The "targeted program of experiments" described in the 2007 Plan has blossomed, leading to both important scientific results and paving the way for profound discoveries and key insights during the next decade. In particular, results from the current generation of searches for the neutrinoless double beta-decay ($0\nu\beta\beta$-decay) experiments in which U.S. nuclear physicists have played leadership roles, along with corresponding technical progress, have set

the stage for U. S. leadership of the next generation, tonne-scale search experiments. The U.S.-led search for a permanent electric dipole moment of the neutron has passed the essential technical milestones that put it on the path to two-orders of magnitude improvement in sensitivity. Ultra-precise measurements of parity-violating asymmetries in neutron decay and electron-proton scattering have provided new tests of possible scenarios for the new Standard Model and opened the door to even more sensitive precision tests in the future.

The opportunities made available by this progress now take on added significance in light of results from experiments at the high-energy and cosmic frontiers. The observation of the Higgs-like particle at the CERN Large Hadron Collider fills in the remaining piece of the Standard Model, but with the non-observation of any other new particles the question of how to advance beyond it remain open. Given the challenges associated with new particle searches at the hadronic collider, it is possible that the new interactions involve relatively light degrees of freedom whose effects would first appear in high sensitivity fundamental symmetry tests and neutrino property studies. The prospect that cosmology becomes sensitive to the sum of masses of the neutrinos further underscores the importance of terrestrial measurements of neutrino masses and studies of their interactions. A mis-match between results from these two frontiers could yield important insights about the role played by neutrinos in the early universe.

The prospects for fundamental discoveries and deep insights into the laws of nature through fundamental symmetry tests and neutrino studies has generated a growing level of enthusiasm since the 2007 Long Range Plan. Realizing the opportunities for the next decade then calls for an enhanced level of support for both experimental and theoretical initiatives as well as a major investment in a next generation $0\nu\beta\beta$-decay search that could yield a Nobel-prize caliber discovery. This two-pronged vision for the next decade is reflected by the two recommendations emerging from the Town Meeting, included here with explanatory text:

> The opportunities for nuclear science to address deep mysteries surrounding natures fundamental interactions are unprecedented. The nature of the neutrino, the origin of the cosmic matter-antimatter asymmetry, the composition and interactions of dark matter, and the stability of the electroweak scale cannot be explained within the Standard Model of fundamental interactions. Nuclear physics studies of neutrinos and tests of fundamental symmetries provide a unique opportunity for addressing these questions. Over the past decade there has been a focused and successful program developing new ideas and methods for achieving these objectives.

- **Recommendation:** *Building on recent results and progress, we recommend an enhanced program of experiments and theory in fundamental symmetries and neutrinos designed to determine the masses and other properties of neutrinos, search for yet unseen violation of time reversal invariance and lepton number conservation, and reveal interactions beyond the Standard Model.*

  Advancing this portfolio of experiments and theory will require concomitant support for research, including Major Items of Equipment. The establishment of a standing NSAC subcommittee charged with advising the agencies on the ordering and development of specific experimental opportunities over the full range of the field of fundamental symmetries and neutrinos would help assure the overall effectiveness of enhanced funding. Increased support for related theoretical efforts through a targeted topical collaboration, establishment of a theory-driven topical center with a focus in this area of research, and implementation of an initiative in computational physics across the field of nuclear theory would be essential components of this program.

- **Recommendation:** *As our highest priority for major construction, we recommend that the US lead the development and deployment of a tonne-scale neutrinoless double beta decay experiment*

  A tonne-scale search for neutrinoless double beta decay would provide the opportunity for a major discovery, lepton number violation, at a sensitivity level consistent with the neutrino mass inverted hierarchy. Such a discovery would have profound ramifications for our understanding of the origin of the cosmic matter-antimatter asymmetry, the way in which neutrinos acquire mass, and the role of neutrinos in the early universe.

In the remainder of this White Paper, we provide the background for these recommendations and flesh out the opportunities for the next decade. With the 2007 NSAC Long Range Plan the nuclear physics community has embarked on an exciting endeavor whose ramifications go far beyond the scope of the field. Now is the time to capitalize on this progress and propel the field into an even richer future of discovery and insight.

II. INTRODUCTION

Nuclear physics tests of fundamental symmetries and studies of neutrino properties have yielded some of the most important insights into the fundamental laws of nature. From the observation of parity-violation in the β-decay of ^{60}Co through the observed deficit of solar neutrinos in Ray Davis' chlorine detector and the subsequent observation

of neutrino oscillations in the SNO and KamLAND experiments, these studies have discovered key ingredients of the Standard Model (SM) of fundamental interactions and the emerging "new Standard Model" that will encompass it. Over this history, nuclear physics experiments have severely constrained and, in some cases, ruled out some possibilities for the new Standard Model (NSM) while motivating proposals for others. The stringent limits obtained on the permanent electric dipole moment of the neutron, for example, imply that the strength of CP violation in the SM are vanishingly small, suggesting the existence of a new symmetry (Peccei-Quinn) and the associated axion that may comprise the abundance of cold dark matter in today's universe.

This subfield of nuclear physics has entered a new and exciting era. The corresponding potential for both discovery and insight was recognized by the nuclear physics community in its 2007 NSAC Long Range Plan, promoting fundamental symmetry tests and neutrino studies to one of the four primary research thrusts of the field. This development reflected a recognition that the subfield is an integral part of the nuclear physics scientific mission, that it provides unique opportunities for obtaining results having far-reaching significance, and that this potential is highly complementary to that of related disciplines, such as high energy physics and cosmology. Since 2007, the subfield has flourished, achieving important advances in addressing questions left open by the SM, setting the stage for even more significant results, and attracting new talent into the field. As a result, the opportunities provided by the "targeted program of experiments" described in the 2007 Long Range Plan have both matured and expanded in ways described throughout the remainder of this white paper.

In addressing these opportunities, it is important to place them in the larger contexts of the quest for a new Standard Model and of the nuclear science mission. Developing the new Standard Model is, of course, a task that reaches across the lines of various subfields of physics, sometimes characterized in terms of various "frontiers". With the discovery of the Higgs-like particle at the Large Hadron Collider, experiments at the high energy frontier have largely confirmed the last remaining prediction of the SM. On the other hand, the non-observation of any other new particles at the Tevatron and LHC leave unanswered key questions that the SM does not address, such as: Why is there more matter than antimatter in the present universe? What comprises the cold dark matter? What mechanism ensures stability of the electroweak scale against quantum corrections? Importantly, null results (to date) of LHC new particle searches suggest that insights into these questions may not soon be found at the high energy frontier. Against this backdrop the low-energy, high-sensitivity fundamental symmetry tests and neutrino studies at the nuclear physics frontier take on added significance. Perhaps, as with the discoveries of parity violation and neutrino oscillations, the first indications of answers to the key open questions will emerge from nuclear physics.

Fundamental symmetry tests and neutrino studies (FS & N) are equally vital to the nuclear physics scientific mission: "to explain, at the most fundamental level, the origin, evolution, and structure of the visible matter of the universe," at the heart of which are atomic nuclei. The FS & N program bears on all aspects of this enterprise. The origin of the visible matter, characterized by the cosmic matter-antimatter asymmetry, cannot be explained within the SM alone. The next generation searches for the neutrinoless double β-decay of atomic nuclei and for the permanent electric dipole moments of the neutron and neutral atoms may discover essential ingredients in achieving this explanation. The evolution of the visible matter, from the time before quarks and gluons were confined in hadrons through the generation of heavy elements, is inextricably tied to the interactions within the SM as well as those that may be part of the NSM. Precise measurements of parity-violating asymmetries in electron scattering and β-decay, as well as other observables that are not precluded by SM symmetries, can reveal the "footprints" of interactions that may be part of the NSM. Understanding the structure of the visible matter, from the internal landscape of quarks and gluons inside nucleons, through the crusts of neutron stars, to the dynamics of stars and the structure and distribution of galaxies, is both exploiting FS & N studies as probes as well as utilizing results to constrain theoretical descriptions.

In short, both within and beyond our discipline, nuclear physics tests of fundamental symmetries and neutrinos provide exciting opportunities for major discoveries and key insights into the basic laws of nature and their realization in nuclear matter. These opportunities were recognized by the participants in the September 2014 Town Meeting on Fundamental Symmetries, Neutrinos, Neutrons and Related Nuclear Astrophysics, leading to the two primary recommendations appearing in the Executive Summary.

Primary recommendations: background and discussion. Several elements of these recommendations merit further amplification here as well as pointers to the remainder of this White Paper. These recommendations reflect, first of all, the growth of the subfield and the corresponding opportunities. The first recommendation notes that if we are to capitalize on the advances made since the 2007 NSAC LRP, it is essential to enhance investment in both theory and experiment. While experimental initiatives have been emphasized since the 2007 NSAC LRP, it is important to enhance support for theory as well as experiment, since theory is essential to both interpreting experimental results and setting the future direction of the program. Supporting growth for the subfield as a whole will also require restoring the balance of research and operations for nuclear physics, an issue that cuts across all the sub-areas and that is particularly vital to this one, which has no single laboratory as its "home" and which lives to a greater extent than some others on research. A particularly important component of the research allocation is the opportunity for new experiments to be funded as Major Items of Equipment.

Beyond enhanced research support for both experiment and theory, the community recommends the establishment of a standing NSAC subcommittee to advise the funding agencies on the "ordering and development" of the experimental program across the subfield. This recommendation reflects the experience from the past seven years, when two NSAC subcommittees were charged with addressing particular components of the program: fundamental physics with neutrons and neutrinoless double β-decay ($0\nu\beta\beta$). In the 2007 NSAC LRP process, a significant effort was made to prioritize the science in broad terms, thereby providing agencies with the outlines of a program but not specifying details of ordering or relative priority among various experiments. It was clear that in some areas significant R&D was needed in order to be able to make good decisions. With much of that accomplished, more detailed guidance is needed now, particularly in the presence of constrained resources and a need to prioritize across specializations. The NSAC neutron physics subcommittee, which developed a snapshot in time of opportunities in fundamental neutron physics and developed an ordered set of priorities, could serve as an example for a such a standing NSAC subcommittee for fundamental symmetries and neutrinos generally.

The foregoing issues – the high dependence on research support and the absence of the equivalent of a laboratory Program Advisory Committee – point to another feature of the subfield that is both a strength and a challenge: the absence of any single facility to which it is anchored and from which it has a focal point. The benefit of this situation is flexibility in pursuing scientific opportunities that require technologies available at different facilities and that may emerge in a time-sensitive fashion. The downside is the absence of an intellectual center where both experimentalists and theorists may interact, develop new ideas, refine existing approaches and set the direction for the future – much as might occur at a national laboratory with its resident theory group. The establishment of a modest-scale topical center for fundamental interactions that would function in this capacity would address this need. An example is currently being prototyped at the University of Massachusetts Amherst[1](see Sec. XII), and one would anticipate a long-term center resulting from an open, nationally competitive process.

As described in Sec. XII, the theoretical effort in FS & N is relatively under-supported compared to other subfields of nuclear physics. While this situation was, perhaps, tenable prior to 2007, the subsequent growth of the experimental program has made the need for enhanced theoretical support abundantly apparent. Beyond the establishment of a topical center, there exist a variety of mechanisms for addressing this need, including the Topical Collaborations initiative that was launched in response to the 2007 LRP. Expansion of the Topical Collaborations initiative, with inclusion of one targeted for this subfield, would provide one avenue for growing the theoretical effort. It is also important to recognize that many of the theoretical problems interface with those in nucleon and nuclear structure. Consequently, implementation of the nuclear physics-wide initiative in computational physics would assist the FS & N theoretical effort, assuming the core workforce and support needs are adequately addressed.

Neutrinoless $\beta\beta$-decay searches	Electric Dipole Moment searches
Lepton number conservation, nature of the neutrino, origin of matter	*CP violation in & beyond the SM, origin of matter*
Lepton Properties and Interactions	Weak Decays & Other Tests
SM precision tests, probes of new interactions, probes of QCD & many-body dynamics	*SM precision tests, probes of new interactions, probes of QCD & many-body dynamics*

TABLE I: Four primary thrusts for the experimental program of fundamental symmetry and neutrino studies. For each area, the primary physics being addressed is indicated in italics.

A particular highlight of the post-2007 FS & N program has been the ground paved for a tonne-scale $0\nu\beta\beta$ experiment. The scale of resources required for such an experiment is nearly an order of magnitude beyond any of the existing FS & N experiments, an investment the community believes is easily justified by its discovery potential. As with the discovery of CP violation in the neutral kaon system of neutrino oscillations in recent years, the discovery of total lepton number violation *via* the observation of the neutrinoless double β-decay of a nucleus would be Nobel-prize caliber. The community recommends that the U.S. lead the effort to develop such an experiment, which is likely to be ready for construction during the next several years. Recognizing that launching this endeavor of this scale would represent a new paradigm for nuclear physics, NSAC has established a standing committee to evaluate the possible technologies for it and recommend a choice when one or more has matured. The results of the first phase of this committee's work has been separately published (*http://science.energy.gov/np/nsac/reports/*), and we refer readers to it for detailed background. In addition, given the nature of this opportunity, a somewhat longer section is being

[1] http://www.physics.umass.edu/acfi/

devoted to both the physics and the experimental development for a tonne-scale $0\nu\beta\beta$ experiment than for other initiatives discussed in the White Paper.

Overall, the opportunities for the next decade can generally be classified into one of the four components identified in Table I. Along with theory, related areas of nuclear astrophysics cross some of these components. Here we highlight the primary physics objectives for each area and the major opportunities for the coming decade:

- *The search for $0\nu\beta\beta$ decay:* The observation of this process would constitute a major discovery, indicating that total lepton number is not a good symmetry of nature and that neutrinos are their own antiparticles, a key ingredient for explaining the cosmic baryon asymmetry through the process of leptogenesis.

  The community recommends that the U.S. lead the development of the next-generation, tonne-scale $0\nu\beta\beta$-decay search, building on the current set of U.S.-supported experiments.

- *Searches for permanent electric dipole moments*: The observation of a non-vanishing permanent electric dipole moment (EDM) of the neutron, neutral atoms, and/or polar molecules would also constitute a major discovery, revealing the existence of CP violation in the Standard Model strong interaction and/or new sources of CP violation beyond the Standard Model. The latter are an essential ingredient for explaining the cosmic baryon asymmetry, and their observation could indicate that it was created during the era of electroweak symmetry-breaking.

  The flagship U.S. nuclear physics effort is the search for a permanent EDM of the neutron at the Spallation Neutron Source Fundamental Neutron Physics Beamline located at Oak Ridge National Laboratory. The experiment is on track to yield the world's most sensitive neutron EDM search during the next decade, improving over the current sensitivity by two orders of magnitude.

  Other important components of the present and prospective U.S. nuclear physics program include searches for the EDMs of the diamagnetic atoms ^{225}Ra and ^{199}Hg. U.S. nuclear physicists are also playing leading roles in the searches for the EDMs of ^{223}Rn at TRIUMF and ^{129}Xe in Munich. Members of the community are also involved in developing a storage-ring based search for the proton EDM.

- *Lepton properties and interactions*: This component of the program address primarily three questions: What is the absolute scale of the active neutrino masses? What are the "footprints" of possible new BSM interactions? And what role do neutrinos play in, and what information can they provide regarding, astrophysical process? The effort to determine the neutrino mass scale focuses on kinematic effects in nuclear β-decay. The KATRIN tritium β-decay experiment is on track to probe the mass scale at the 0.2 eV sensitivity within the next decade. During that time, efforts to develop more sensitive kinematic techniques using MAC-E filters (NuMECS) or frequency measurements (Project 8) should be pursued.

  Precise measurements of charged lepton properties and interactions probe possible new interactions that may arise in the new Standard Model. Significant new investments include a measurement of the parity-violating asymmetry in Møller scattering and in deep-inelastic electron-deuteron scattering with the 12 GeV beam at Jefferson Laboratory. Members of the U.S. nuclear physics community are also leading the effort for a new measurement of the muon anomalous magnetic moment at Fermilab. Looking to the future, a search for charged lepton flavor violation (CLFV) *via* e to τ conversion at an Electron Ion Collider could complement other CLFV searches with muons at Fermilab and abroad.

  Understanding the interactions of neutrinos with nuclei is fundamentally a nuclear physics problem, with efforts in different energy regimes driven by nuclear physics community members. Coherent elastic neutrino-nucleus scattering is a Standard Model probe, and there are opportunities to measure it and other interactions in the regime relevant for supernova neutrinos at the Spallation Neutron Source. This is also an important area of interface with high-energy physics. The future HEP program, such as the Long-Baseline Neutrino Experiment (LBNE), involves accelerator-produced beams of neutrinos, and will turn to NP for information about neutrino interactions with nuclei.

  A particularly timely opportunity is the possibility of a period of liquid scintillator running with the SNO+ detector at SNOLAB, providing unique sensitivity to CNO solar neutrinos and helping to resolve the "Solar Metallicity Problem". Enabling a solar neutrino phase with this detector is an ideal investment for U.S. nuclear physics, leveraging international investment in order to address a fundamental area of nuclear astrophysics.

- *Weak interactions and other tests*: Low-energy weak interactions provide an increasingly powerful window on possible new interactions as well as poorly-understood aspects of the Standard Model. Exploiting new capabilities at the Fundamental Neutron Physics Beamline, new measurements of decay correlations in neutron β-decay will provide unprecedented probes of possible new scalar and tensor interactions, complementing direct

searches at the LHC. These studies, along with developments using ^{6}He, will open the door to future, order-of-magnitude sensitivity improvements. New approaches for measurements of the neutron lifetime using beam experiments, together with refinements of stored ultra cold neutron (UCN) measurements, aim to resolve the present 4σ discrepancies between the results of beam and UCN lifetime determinations. Studies of parity-violating asymmetries with polarized neutrons at the Fundamental Neutron Physics Beamline, the new NG-C beam line at NIST, and possibly the HIγS facility at the Triangle Universities Nuclear Laboratory will provide new probes of the short-distance strangeness conserving, hadronic weak interaction in the few-body system. These experiments will complement the recently completed measurement of the asymmetry for polarized neutron capture in hydrogen that probes the long-range, one-pion exchange component.

Other opportunities include searches for long-range, non-Newtonian forces using neutrons and polarized ^{3}He. Searches for very light, weakly coupled neutral bosons ("dark photons") using the Jefferson Lab ERL will significantly extend the coupling sensitivity.

A detailed discussion of these and other opportunities is given in the remainder of the White Paper, following a short summary of accomplishments achieved since the 2007 NSAC LRP. In laying out these opportunities, we note that there exist several topical areas of potential overlap between efforts supported by the nuclear physics programs at the Department of Energy and National Science Foundation and those supported by the corresponding high energy physics (HEP) programs. A discussion of this interface, which is particularly pronounced for some elements of the neutrino and muon physics programs, is given in Section V (see also Tables II and VII as well as Fig. 11). Some of the proposed new initiatives (see Section X) involve HEP-funded research at nuclear physics facilities or involvement of nuclear physics-supported personnel in initiatives primarily funded by HEP. For these areas of overlap, we endeavor to delineate those that would naturally fall primarily under the nuclear physics purview, even where the broader scientific questions cross funding agency field delineations.

III. RECENT ACCOMPLISHMENTS: HIGHLIGHTS

The past decade has been a period of discovery and progress in the field of Fundamental Symmetries and Neutrinos. In this section we mention just a few of those highlights.

A. Are neutrinos their own antiparticles?

- The EXO [1], KamLAND-Zen [2], and GERDA [3] double beta decay detectors have essentially ruled out a long-standing claim for observation of the neutrinoless decay mode in ^{76}Ge.
- The first measurement of the 2-ν double beta decay of ^{136}Xe was made by the EXO Collaboration [4].
- The CUORE Collaboration [5] has brought the world's largest-volume dilution refrigerator to base temperature [6], a major step towards a ton-scale bolometric experiment.
- The Majorana Demonstrator Collaboration has reported record Cu purity [7] from its underground electroforming campaign, and expects to achieve the ultra-low backgrounds specified. Commissioning runs with more than 10 kg of highly enriched ^{76}Ge are beginning in the SURF laboratory.
- The SNO+ experiment has demonstrated the stable suspension of $\beta\beta$ isotopes in the scintillator Linear Alkyl Benzene [8], another path toward a ton-scale experiment.

B. Search for electric dipole moments

- A new, stringent limit on the electric dipole moment of ^{199}Hg from the University of Washington group [9], has improved the sensitivity for the most precisely measured EDM limit by nearly a factor of seven.

C. Neutrino mass

- The largest experiment ever conceived for measuring neutrino mass via the beta decay of tritium, KATRIN, has successfully passed commissioning phases demonstrating resolution and efficiency, and is nearing startup in 2017 [10].
- A new concept for electron spectroscopy that is expected to be applicable to neutrino mass measurement, cyclotron radiation emission spectroscopy [11], has been successfully demonstrated [12].

D. Muon Physics

- The US led MuLan experiment measured the muon lifetime τ_μ to the 1 ppm level [13]. This allows one to extract G_F at the 0.5 ppm level.
- The US led MuCap experiment measured g_p, the weak pseudoscalar coupling, confirming for the first time the low-energy QCD-based theoretical prediction [14].

E. Electron Scattering

- First direct measurement of the weak charge of the proton in parity-violating elastic electron-proton scattering [15]. Sufficient statistics was accumulated for the most precise low energy measurement of the weak mixing angle.
- New measurement of parity-violating deep inelastic electron-deuteron scattering with sufficient precision and accuracy to demonstrate that the axial-vector electron-quark weak neutral current couplings are non-zero [16].

F. Search for beyond-standard-model effects in the weak interaction: nuclei

- Numerous meticulous measurements of superallowed $0^+ \to 0^+$ beta decay, which have resulted in the most precise current value for V_{ud} and the most stringent limits on scalar couplings [17, 18].
- Experimental validation of calculated isospin symmetry breaking effects in a system with structure corrections over an order of magnitude larger than any previously studied superallowed Fermi decay [19].
- Development of the strongest ^{6}He source in the world, most precise measurement of the half-life of ^{6}He, and implementation of laser optical trapping of metastable ^{6}He for weak interaction studies [20].
- Measurement of the electron-neutrino asymmetry in ^{8}Li decay in an rf-ion trap [21], with a measurement at the 1% level in preparation by the ANL-LLNL collaboration
- New measurements of mirror decay half-lives, with over an order of magnitude improvement for some species [22, 23], and sub-percent precision for *in situ* optical polarimetry of laser-trapped ^{37}K.

G. Search for beyond-standard-model effects in the weak interaction: neutrons

- First measurement of radiative decay of the neutron [24].
- Determination of the most precise limits on time-reversal non-invariance in beta decay by the emiT collaboration [25].
- Development at LANL of one of the strongest UCN sources in the world[26] and measurement of the beta asymmetry, with current precision at the 1% level [27–29].
- Technological advance in the measurement of the neutron lifetime with cold neutron beams at NIST and an improved cold neutron beam measurement of the lifetime [30].

- Successful demonstration of a magneto-gravitational trap for a neutron lifetime measurement with UCN at LANL [31].
- Successful commissioning of the FNPB beamline at the SNS in preparation for the Nab angular correlation measurement [32].
- Upgrade of the fundamental physics beamline at NIST, ultimately for an order of magnitude improvement in avaiable flux on the NG-C beamline and commissioning of the aCORN experiment [33].

H. Search for beyond-standard-model effects in the weak interaction: mesons

- The PEN and PIENU [34] experiments, at PSI and TRIUMF, respectively, have recently acquired data on pion leptonic decays sufficient to determine $R^{\pi}_{e/\mu} = B(\pi \to e\nu)/B(\pi \to \mu\nu)$ at sub-10^{-3} precision level in the near future, thus enabling new limits on certain non-SM couplings at levels competitive to and complementary with those reached at collider facilities.

I. Search for beyond-standard-model effects in the weak interaction: theory

- New, state-of-the art tools have been developed for computing the cosmic matter-antimatter asymmetry and have been applied to the confrontation of supersymmetric models with limits on electric dipole moments [35–44].
- Development of a pion-nucleon effective field theory of T- and P-violating interactions, leading to a DNP Thesis Prize[45, 46]
- A comprehensive analysis of beta-decay observables within the Minimal Supersymmetric Standard Model [47–50] and the development of a unified treatment, based on effective field theory (EFT), of probes for BSM physics which permits model-independent comparisons between the sensitivity of collider experiments and low energy precision measurements [51–53].
- Improved prediction of the ratio $R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ using two-loop chiral perturbation theory [54].
- Development of precise calculations of the form factors of the nucleon using lattice QCD [52, 55, 56].
- Development of an explicit prescription to analyze beta decay correlations to constrain BSM physics [57], and identification of new triple product correlations in radiative beta decays as probes of CP violation [58].

J. Search for a dark sector

- In a feat of accelerator engineering, the DarkLight experiment carried out a successful test [59] in 2012 where a 0.43-megawatt, 100-MeV electron beam was passed through an aperture of diameter 2 mm and length 127 mm with 6 ppm losses.

K. Astrophysical nuclear and neutrino physics

- Neutrinos from the ^{7}Be, *pep*, and the primary proton-proton fusion process in the Sun have been observed for the first time in the Borexino solar neutrino detector in Gran Sasso [60–62].
- From the observable properties of neutron stars it has been possible to draw definitive conclusions about the nuclear equation of state at densities higher than found in nuclei [63].
- A new phenomenon of importance to both neutrino physics and supernova physics has been analyzed theoretically, the nonlinear collective interactions of neutrinos with each other in the dense environment of an exploding stellar core [64].

IV. SUMMARY OF PROJECTS

In the sections below, the research planned for this field is set forth in detail. As an introduction to the detailed descriptions, the projects advanced for consideration at the Town Meeting are summarized in Table II. In this table, the status of projects is considered to have 5 stages, Concept (a general idea exists and is being investigated with theory and simulations), R&D (specific aspects are being explored in hardware), Planning (a design has been settled on and prepared for a proposal), Construction (funding and building), and Data Taking (commissioning included).

V. INTERFACE WITH HIGH ENERGY PHYSICS

To provide a useful context for what is to follow, we discuss at this point the relationship between Nuclear Physics (NP) and High Energy Physics (HEP) as it bears on the scientific goals of this field. There is significant overlap between the NP community and the HEP community in the US and worldwide. Nowhere is this more evident than in the field of FS&N. The Standard Model is the foundation of our understanding of all physical science. Some fields, for example biology and chemistry, make use of established parts of it that are necessary for their research, such as electromagnetism in those cases. But NP and HEP are charged with finding the limits of the SM and using that information to develop the New Standard Model, still more comprehensive and powerful in its ability to describe all of nature.

It might be thought that the common objective of the two fields must translate into duplication of effort. The following points are relevant to that question:

- There are many cases where expertise from one community helps push forward progress in the other. As an example, properties of nuclei need to be understood in order to interpret the results of neutrino experiments; accelerator produced neutrinos can in turn be used as probes of nuclear physics.
- The problems studied in FS&N are in most cases difficult, and many require the combined expertise of both HEP and NP physicists. Each community brings different skills to the table. The first and only definitive example of a prediction of the Standard Model disagreeing with data was the discovery of neutrino mass and oscillations. This physics in turn resolved the long-standing solar neutrino problem. It required the combined effort of NP and HEP physicists.
- The two communities may approach a particular question in very different ways. If a discovery is made, its significance demands confirmation, and the differences in approach bring valuable certitude.
- The communities collaborate, but they also compete for discovery. Competition differs from duplication, leading to better results obtained more quickly.

The HEP community has recently completed major planning and prioritization exercises. The massive 2013 "Snowmass" activity, driven by the community and led by the APS DPF, identified the most compelling scientific opportunities over the next approximately 20-year time frame. This exercise included many members of the NP FS&N community, and considered many of its flagship projects as well [65]. In 2013/2014, the Particle Physics Project Prioritization Panel (P5), a subcommittee of HEPAP, used the Snowmass material as input to fulfill its charge to select the highest-priority large-scale projects within well-defined budget scenarios. Its report [66] was accepted in May 2014 and included 29 recommendations, a number of which were relevant to this NP community. Among the most important criteria for project selection were five unprioritized "Science Drivers". Connections to NP science and technology can be found in all of them, but the largest overlap is with the following two:

- "**Pursue the physics associated with neutrino mass.**" At least two of the essential questions identified with this science Driver, "What are the neutrino masses?" and "Are neutrinos their own particles?" are central to this NP community. Neutrinoless double beta decay searches were explicitly called out: *An important example is provided by neutrinoless double-beta decay experiments, which address one of the most significant questions in the neutrino Driver and which are stewarded in the U.S. by the DOE Office of Nuclear Physics, with construction contributions also from NSF Particle Astrophysics. Modest levels of support by the U.S. particle physics funding agencies for particle physicist participation in such experiments, as well as in experiments hosted by other nations without major U.S. construction investments, can be of great mutual benefit.* ***Recommendation 9: Funding for participation of U.S. particle physicists in experiments hosted by other agencies and other countries is appropriate and important but should be evaluated in the context of the Drivers and the P5 Criteria and should not compromise the success of prioritized and approved particle physics experiments.***

Projects	Status (Jan 1, 2015)	Total Cost ($ M) (U.S. sources)	Comment	Request	Location
NEUTRINOLESS DOUBLE BETA DECAY					
CUORE	Construction		Italy + US ops	Operations	LNGS
EXO	Data Taking		HEP/ now NP	Operations	WIPP
Majorana Demonstrator	Construction	21	DOE NP	Operations	SURF
KamLAND-Zen	Data Taking		Japan + US ops	Operations	
SNO+	Construction		Canada + US ops	Operations	SNOLab
TonneScale 0vbb	Concept, R&D	n x 100	Extrapolations	Project funding	TBD
ELECTRIC DIPOLE MOMENTS					
Hg-199	Data Taking		NSF	Operations	UW
nEDM	R&D, Planning	45	NSF Midscale +?	Project funding	SNS
Radium-225 EDM	Data Taking		DOE ops	Operations	ANL
p EDM storage ring	Concept	70	HEP+NP ops ?		BNL
nEDM at LANL	R&D	< 5		Project funding	LANL
NEUTRINO MASS					
KATRIN	Construction		DOE NP	Operations	KIT
Project 8 Phase 1	Data Taking		DOE ops	Operations	UW
Project 8 Phases 2-4	Concept			Project funding	
NuMECS	Concept			Project funding	LANL/FRIB
NEUTRINOS					
MINERvA	Data Taking			Operations	FNAL
CAPTAIN	Planning			Project funding	FNAL
CENNS	Planning			Project funding	FNAL
COHERENT	Planning			Project funding	SNS
BSM: NUCLEI					
He-6 little b	R&D	2	estimate	Project funding	UW
Li-8 beta decay	Data Taking		DOE NP	Operations	ANL
32-Ar beta decay					
ALPHA2	Data taking			Operations	CERN
BSM: NEUTRONS					
Nab	Construction	4	NSF MRI	Operations	SNS
aCORN	Data Taking				
npdgamma	Complete			Operations	SNS
nHe3				Operations	SNS
UCN Tau			LDRD	Operations	LANSCE
n Lifetime			NIST +	Operations	NIST
UCNA/UCNB	Data Taking/Planning		pending upgrade	Operations	LANSCE
BSM: LEPTONS					
Muon g-2	Construction	50	HEP + MRI	Operations	FNAL
Moller	Planning			Project funding	Jlab
SoLID	Planning			Project funding	JLab
Heavy Photon Search	Data Taking			Operations	Jlab
DARKLIGHT	Construction		MRI support	Operations	JLab
$e \to \tau$ CLFV	Planning				EIC
ASTROPHYSICS					
MuSun	Data taking	0.5	grants + intl.	Operations	PSI
CLEAN	Planning			Project Funding	
PINGU	Planning		NSF	Operations?	SouthPole
THEIA	Concept, R&D				
THEORY					
FS&N Center	Planning	0.3		Operations	TBD

TABLE II: Current and planned projects and initiatives in the field of FS&N.

- "**Explore the unknown: new particles, interactions and physical principles**." This P5 science driver encompasses many other activities which are being vigorously pursued by members of the NP FS&N community, including baryon and lepton number violation searches, muon anomalous magnetic moment, and electric dipole moment measurements, supernova physics, and searches for "dark photons" (low-mass "hidden sector" particles).

Another P5 recommendation of potential relevance to this community, given that it includes a number of diverse, relatively smaller-scale activities, is "***Recommendation 4: Maintain a program of projects of all scales,***

from the largest international projects to mid- and small-scale projects. Here the idea is to ensure that smaller-scale projects (less than $20M) can still thrive even when very much larger projects are the highest priority.

Countries, and within them Agencies, have developed a variety of means for administering research that may not fit neatly into a granting Office. In the US, NSF handles NP and HEP both from the Mathematical and Physical Sciences Directorate, and certain areas of neutrino physics are considered Particle Astrophysics. DOE has also developed operational definitions of which research belongs in which Office (NP or HEP). For example, Dark Matter searches are HEP, Neutrinoless Double Beta Decay searches are NP, neutrino physics with natural sources (the sun, radioactive nuclei, supernovae, etc.) are NP, artificial sources (accelerators, reactors) are HEP, and so forth. Such divisions seem arbitrary but allow the agencies to gather similar efforts under one umbrella, facilitate peer review, and prevent duplication. For the most part, the Agencies have viewed the divisions with some flexibility when a situation called for it. In Section VIII tables are given that organize the neutrino and muon projects according to the principal community driving each.

Members of both communities sometimes express concern that their activities are hindered by "stovepiping", i.e., when research genuinely straddles boundaries of traditional agency stewardship, it can be difficult to find funding. However, with attention and effort, such issues have been solved in the past. It is critical for members of HEP and FS&N (and other) communities to persist in finding constructive solutions in collaboration with the agencies.

VI. TONNE-SCALE NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENTS

A. Introduction

Conservation of lepton number has been observed in every measured microscopic process. Yet within the Standard Model, lepton number is an accidental symmetry—other fundamental symmetries, such as charge conservation, preclude processes that can change leptons into antileptons (or vice versa). With the discovery of neutrino mass and flavor mixing, however, the picture is dramatically changed. Neutral, massive, fundamental fermions can be Majorana particles, and make lepton-number-violating processes possible. The most powerful and comprehensive way to demonstrate the Majorana nature of neutrinos is through searches for neutrinoless double beta decay ($0\nu\beta\beta$), a nuclear decay made possible by the nuclear pairing force, in which electrons but no neutrinos are emitted, thus explicitly violating lepton number conservation. If such a process were observed, it would not only show that neutrinos are fundamental Majorana fermions and that lepton number was violated, but it would also have implications for physics at the highest energy scales and perhaps even explain the origin of the asymmetry between matter and antimatter in the Universe.

We live in an exciting era for neutrinoless double-beta decay searches. An explosion of creativity by nuclear physicists over the past several years, driven by the compelling question of whether lepton number is violated, has led to a broad range of detector technologies, each with a distinct approach. The technical developments associated with the pursuit of $0\nu\beta\beta$ are themselves great achievements: creation of ultra-pure materials, powerful, large-scale cryogenic facilties, novel tracking devices, and new event reconstruction and particle identification algorithms. These experiments, which are either already operational or coming online in the next year or two, are sensitive to $0\nu\beta\beta$ lifetimes in the range of 10^{25}–10^{26} years, and will provide us with a wealth of information about how best to take the next steps, while also training young scientists in the US and abroad.

Next-generation $0\nu\beta\beta$ experiments have a great opportunity to discover this extremely rare process. With masses of isotope on the scale of tonnes, expected improvements in lifetime sensitivity are two orders of magnitude or more over existing limits. Such "tonne-scale" experiments can therefore discover $0\nu\beta\beta$ via light Majorana neutrino exchange if the lightest neutrino mass is above $\sim$50 meV, or if the spectrum of neutrino masses is "inverted." Even if neither of these two conditions is respected in Nature, a discovery is possible with next-generation sensitivity if other mechanisms contribute to the decay. With the results from the current generation of experiments, and continued targeted R&D, the path toward building the next-generation detectors will be clear in the next 2-3 years.

Leadership of an experiment at the tonne-scale would give the US Nuclear Physics community an excellent chance of making a Nobel Prize-caliber discovery. With the experience and knowledge gained from the broad existing program of $0\nu\beta\beta$ experiments that have US leadership and significant US involvement, now is the time to make the step toward the next critical sensitivity milestone.

B. Physics Drivers of $0\nu\beta\beta$ Searches

Our view of neutrinos has changed dramatically over the past fifteen years or so, as results from atmospheric, solar, reactor, and accelerator-based neutrino oscillation experiments have provided compelling evidence that neutrinos

change flavor and that this transformation occurs because they are massive and mixed. Such a discovery might seem to require only a modest modification of the Standard Model: neutrino mass could be generated in the same way as every other known fermion, through the mechanism of electroweak symmetry breaking. The absence of charge, however, and the smallness of the neutrino mass makes the picture more complex, and far more interesting, allowing for the violation of lepton number and perhaps an explanation for the asymmetry between matter and antimatter in the Universe. Today, there is no "standard" model of neutrino mass generation, but instead multiple models that can be distinguished only through experiments.

The most straightforward way to include massive neutrinos in the Standard Model Lagrangian might appear to be to indeed treat them as we do other "Dirac" fermions, giving them mass terms through couplings to the Higgs field. Such a description requires a chirally right-handed neutrino ν_R, and a left-handed antineutrino, $\bar{\nu}_L$, increasing the number of neutrino states from two to four. As electroweak singlets, however, these additional neutrino states have no function in the model other than to allow neutrinos to be massive. They participate in no interactions other than their coupling to the Higgs bosons and gravity, and both of those interactions are minuscule on microscopic scales—thus a ν_R (or a $\bar{\nu}_L$) is essentially a sterile state. While mathematically in this model a ν_R is an electroweak singlet and a $\bar{\nu}_R$ is part of a doublet, there is no fundamental physical difference between these states: no known gauge symmetry that distinguishes them. Neutrinos are therefore very different than the electrically charged fermions, such as the electron and positron. The ν_R and $\bar{\nu}_R$ are both right-handed, neutral, spin-1/2 particles with the same mass. To force them to be different we must promote the global—and otherwise completely accidental—symmetry of lepton number, which formally distinguishes leptons from antileptons, to something fundamental. Yet despite the lack of a supporting theoretical motivation, to date lepton number has been observed to be conserved in every measured microscopic process.

A different way of including neutrinos into the Standard Model is to assume that there are indeed just two states—ν_L and ν_R—and that the interactions that appear to proceed via "antineutrinos" are those in which the right-handed chiral state participates. Under such a description, neutrinos are therefore their own antiparticles ("Majorana fermions"), and interactions in which lepton number is violated can occur. (Another global symmetry now known to be violated is lepton flavor number: neutrino flavor transformation clearly violates this symmetry). The Majorana model is not without its own complexity, however. The simplest lagrangian mass term that includes neutrinos as Majorana particles has dimension five and is not renormalizable. Like the early Fermi theory of β decay, such a term would point very clearly toward a deeper, more complete fundamental theory.

Majorana neutrinos would have several intriguing and important consequences. A natural way of explaining the tiny observed neutrino masses is via the "see-saw" mechanism, where a reduction of the mass of the neutrino results from a ratio of Dirac fermion masses to extremely high-mass Majorana states. Thus in this scenario small observed neutrino masses point to mass scales in the Grand Unification range, an energy regime unlikely to be probed by terrestrial accelerators. Thus, Majorana neutrinos may be directly connected to the highest energy scales.

Majorana neutrinos may also violate CP symmetry in new ways, and in so doing help explain the preponderance of nuclear matter over antimatter in the early Universe through the mechanism of "leptogenesis". Therefore, the discovery of lepton number violation and Majorana neutrinos would have profound theoretical implications in the formulation of a new Standard Model, while yielding insights into the origin of mass itself.

The most practical way of determining whether neutrinos are Majorana fermions is by observing the process of neutrinoless double beta decay ($0\nu\beta\beta$), a process that explicitly violates lepton number conservation. The more common process, two-neutrino double beta decay ($2\nu\beta\beta$), has been observed in several nuclei and it is these nuclei that are of primary interest in $0\nu\beta\beta$ searches. If $0\nu\beta\beta$ happens via exchange of light Majorana neutrinos, its rate is given by:

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} g_A^4 \left| M^{(0\nu)} \right|^2 \langle m_{\beta\beta} \rangle^2 \tag{1}$$

where

$$\begin{aligned} \langle m_{\beta\beta} \rangle^2 &= |\sum_i U_{ei}^2 m_{\nu i}|^2 \\ &= |\cos^2\theta_{12}\cos^2\theta_{13} m_1 + \exp^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + \exp^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13} m_3|^2. \end{aligned}$$

As Equation (1) shows, the $0\nu\beta\beta$ decay rate depends on the neutrino masses themselves (m_i), the sizes of the mixing angles (θ_{ij}) and possible phases (λ_2, λ_3, and δ_{CP}), the nuclear matrix element $M^{0\nu}$ and scaling of the axial-vector coupling constant g_A in heavy nuclei (often included in the definition of $M^{0\nu}$), the phase space $G_{0\nu}$ of the particular reaction being studied and, of course, whether neutrinos are Majorana particles or not.

The importance of the question of the neutrino's basic nature, and the need for higher-sensitivity $0\nu\beta\beta$ searches, has been recognized by many panels over the past decade including the 2004 APS Multi-Divisional Neutrino Study,

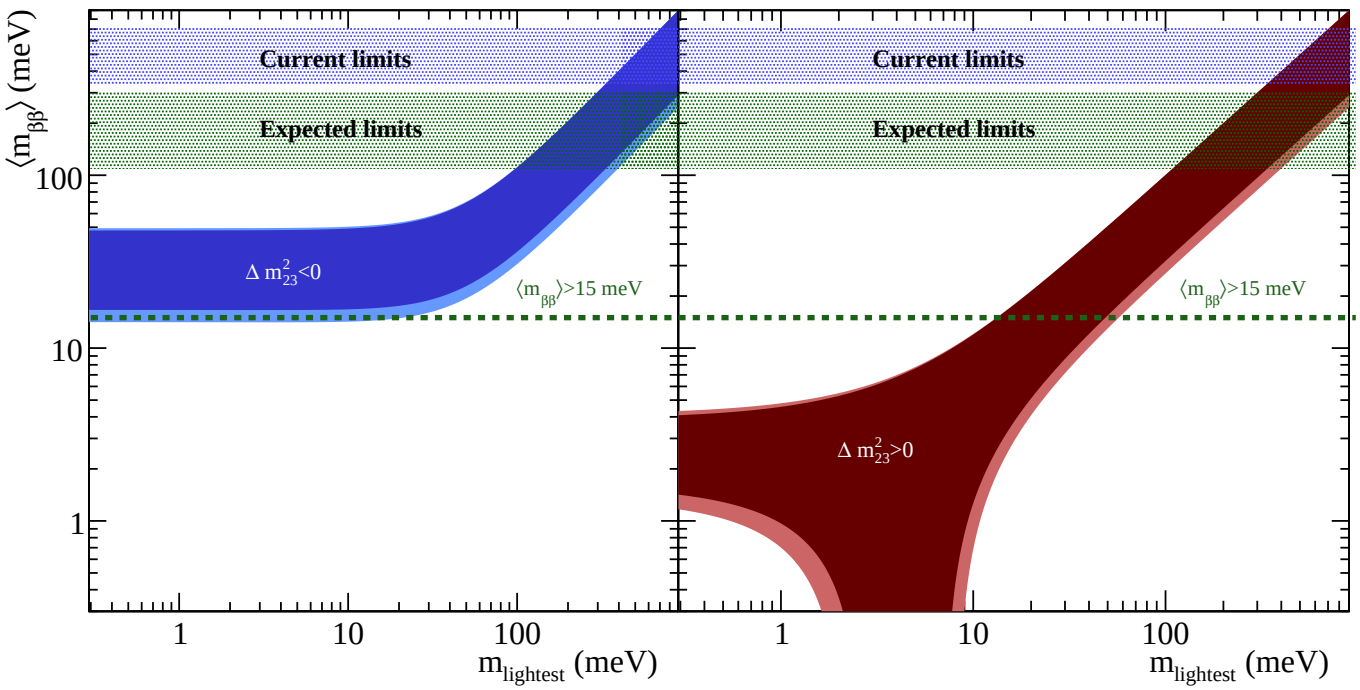

FIG. 1: Allowed values of $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass for the inverted (left) and normal (right) hierarchies. The dark shaded regions correspond to the best-fit neutrino mixing parameters [67] and account for the degeneracy due to the unknown Majorana phases. The lighter shading corresponds to the maximal allowed regions including mixing parameter uncertainties at 90% CL. The blue hatched region at the top indicates the range of existing limits, using the most conservative nuclear matrix elements, also at 90% CL, and the green hatched region indicates the range targeted by current experiments.

the 2005 NuSAG report, the 2006 EPP 2010 study conducted by the National Academy of Sciences, and the 2007 Nuclear Physics Long Range Plan. In its recent April 2014 report the NSAC subcommittee on neutrinoless double beta decay states, "The observation of neutrinoless double beta decay would indeed generate a fundamental shift in our understanding of elementary particles."

C. Sensitivity Goals for Next Generation Tonne-scale Experiments

Since the last Long Range Plan, neutrino oscillation experiments have provided both precision measurements of the splittings between the various m_is as well as the first measurement of the mixing angle θ_{13}. Thus we now have explicit targets for the sensitivity of next-generaration $0\nu\beta\beta$ experiments. Figure 1, which plots the value of $\langle m_{\beta\beta}\rangle$ (upon which $T^{0\nu}_{1/2}$ depends) against the lightest of the m_i, indicates two different scenarios. On the left, we see the case when m_3 is the lightest neutrino, often referred to as the "inverted hierarchy," and on the right the case when m_1 is the lightest mass state, often called the "normal hierachy." Fig. 1 also indicates the range of existing limits from experiments that have already produced results, and the target range for experiments now underway or soon to begin running.

The recent NSAC Subcommittee on neutrinoless double-beta decay recommended that the next-generation experiments should offer a credible path toward reaching a 3σ sensitivity of 15 meV for the effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle$, for even the most conservative of the nuclear matrix elements. Such a limit corresponds to lifetimes of $10^{27}-10^{28}$ years and isotope masses at the tonne-scale, depending on the isotope used. As indicated by the horizontal line in Fig. 1, experiments with this sensitivity would discover $0\nu\beta\beta$ decay if either the mass hierarchy is inverted or if $m_1 > 50$ meV (barring even more exotic physics such as mixing with sterile neutrinos [68]). If lepton number is violated by new TeV-scale physics, leading to significant contributions not directly related to the exchange of light neutrinos, its signature could be found by $0\nu\beta\beta$ experiments regardless of the ordering of neutrino masses.

Should the next-generation experiments not observe $0\nu\beta\beta$, interpretation of the result will be aided by a determination of the mass hierarchy, and by improved calculations of the nuclear matrix elements. The former should be

provided by complementary oscillation experiments that are either ongoing or planned, during or beyond the time period covered by the Long Range Plan. As we describe in Section XII, the latter is the subject of intense effort which we believe will improve the state of the art significantly over the time period of this Long Range Plan. Should m_3 be found to be the lightest state, and should new calculations of the matrix elements not yield values significantly lower than existing calculations, the absence of a signal by the next-generation experiments would demonstrate that neutrinos were Dirac particles, and that lepton number is a fundamental symmetry of Nature, or that exotic non-standard interactions suppress $\langle m_{\beta\beta} \rangle$.

Although knowledge of the size of $\langle m_\beta \rangle$ from the KATRIN experiment could also provide context for a null $0\nu\beta\beta$ result, KATRIN's ultimate goal of $\langle m_\beta \rangle < 200$ meV would correspond to a $\langle m_{\beta\beta} \rangle$ value above or near the upper edge of the inverted hierarchy band. Waiting for the outcome of KATRIN would therefore have little impact on the design of the next generation of $0\nu\beta\beta$ experiments, especially if very small neutrino masses (at the lower edge of the inverted hierarchy band) have to be measured.

Observational cosmology provides important constraints on the sum of the neutrino masses m_{tot}, under a specific set of model assumptions. This exciting field has derived either mass constraints or evidence for the observation of finite neutrino mass, depending on the analysis details and which data are used. The large spread of numerical m_{tot} results at the present time, however, does not allow a quantitative comparison to the proposed experimental sensitivities. Anticipated future improvements to the cosmological data will undoubtedly add significant interest to the quest to understand neutrino properties. Given the dependence on details of both cosmological and analysis models, however, and the great physics interest in comparing and constrasting cosmological and terrestrial mass measurements, improvements in cosmological estimates on $m_{\rm tot}$ are unlikely to have great influence on the planning for next-generation neutrinoless double beta decay searches. A future, robust lower bound on $m_{\rm tot}$ from additional cosmological measurements, coupled with a non-observation of $0\nu\beta\beta$ by tonne-scale experiments, would either be an indication that neutrinos were Dirac particles and that lepton number was a fundamental symmetry, or that our current cosmological models were incomplete. Alternatively, discovery of $0\nu\beta\beta$ with a value of $\langle m_{\beta\beta} \rangle$ inconsistent with the range from cosmological measurements would indicate shortcomings in either the nuclear physics or cosmological models.

The numerical value of the lower edge of the inverted hierarchy band is dominated by the experimental error of the solar mixing parameter (with the atmospheric mass splitting being the next leading error contributor). While a better determination of this mixing parameter by JUNO [69], RENO-50 [70], and/or ELBNF [71] would reduce the uncertainty, the dominant uncertainty in the required experimental exposure still comes from the range of nuclear matrix elements.

There is a consensus within the neutrino physics community that a claim of violation of lepton number conservation would be strongly supported if $0\nu\beta\beta$ was observed in at least two different isotopes, preferably with two different transition energies. Such a dual observation would also mitigate uncertainties related to the modeling of nuclear physics that translates lifetimes into $\langle m_{\beta\beta} \rangle$, and allow details of the $0\nu\beta\beta$ mechanism to begin to be unraveled.

D. Theoretical Considerations

While tonne-scale $0\nu\beta\beta$ experiments have an excellent chance of making a great discovery, a null result nevertheless has significant impact because it will improve the half-life sensitivity by two orders of magnitude over existing limits. Such a major step forward in sensitivity in a rare process search is uncommon.

Interpretation of either a $0\nu\beta\beta$ discovery or a lifetime limit in terms of a neutrino mass scale (or parameters in models with heavy-particle exchange) requires knowledge of the nuclear matrix elements that affect the decay rate. The matrix elements cannot be directly measured and so must be calculated. At present, reasonable calculations differ from one another by factors of two or three, and may all omit important physics. The situation is not unusual for our field, however; the corresponding uncertainty in half-life sensitivity needed to cover the inverted mass hierarchy is analogous to nuclear-theory uncertainties regarding optimal energy ranges at CEBAF (to probe the transition from hadronic to quark-gluon degrees of freedom) and RHIC (to reach the transition to quark-gluon plasma) at the time of past Long Range Plans. Both NuSAG and NSAC reports have wisely recommended the conservative approach of basing $0\nu\beta\beta$ sensitivity goals on the lowest reasonable nuclear matrix elements.

One need not be satisfied with current levels of uncertainty, however, because experimental progress in this field is now galvanizing the nuclear-structure theory community, which is formulating plans to systematically improve matrix-element calculations and quantify their error. A recent meeting of theorists in Darmstadt is leading to a white paper on the subject and an upcoming (March) meeting of the DOE-sponsored SciDAC NUCLEI nuclear-structure collaboration aims to establish benchmarks for evaluating calculations and milestones for improving them in the next few years. The milestones will target meaningful progress, which recent advances in nuclear-structure theory now make possible.

The progress has come in several areas, but perhaps the most promising is in ab initio calculations, those that work with an interaction (typically based on chiral effective field theory) that is fit to few-nucleon data, softened via the similarity renormalization group, and then applied in conjunction with a powerful many-body method such as coupled-clusters theory, the in-medium similarity-renormalization group, or auxiliary-diffusion Monte Carlo (each of which is practiced by some part of the NUCLEI collaboration). Such calculations are now producing reasonably accurate binding energies in nuclei as heavy as tin, and promise to go well beyond those. Though the most accurate calculations are limited at present to a few nucleons outside closed shells, they can be extended to open shell nuclei through a marriage with the shell model. The idea is to use ab initio methods to construct low-lying states in nuclei with one, two, or three nucleons outside closed shells; these states can then be faithfully mapped onto valence-shell states, leading to effective shell-model interactions and decay operators that reproduce the ab initio energies and $\beta\beta$ matrix elements exactly in the few-valence-nucleon systems. Finally, the new interactions and decay operators can be used to calculate the matrix elements in the heavier nuclei, e.g. ^{76}Ge, in which $\beta\beta$ decay actually occurs. Although it is possible that effective four- or five-body operators will make the extension to $A = 76$ difficult, such operators do not appear necessary for spectra in neutron-rich sd-shell nuclei, which were recently reproduced in first applications of these methods with an accuracy comparable to that achieved by traditional shell-model interactions (e.g. the USD interaction) that are fit to sd-shell nuclei themselves. We thus have good reason to hope for success with $\beta\beta$ decay in heavier systems.

The promise of this "ab-initio shell model" does not mean that other methods — the QRPA, the generator-coordinate method (GCM), etc. — will be abandoned; in fact they will be important in heavy nuclei, particularly those with deformation, shape coexistence, or other complicated structural features that may be hard to fully capture in the shell model. Here the primary improvement will come from insuring that all the correlations we know to be important are included. The GCM, at present, mixes states with different amounts of deformation and like-particle pairing, but does not explicitly treat proton-neutron pairing or non-collective excitations; supercomputing will allow these deficiencies to be eliminated. The QRPA, which does include proton-neutron pairing and non-collective degrees of freedom, currently treats particle-hole excitations and pairs as bosons; this "quasiboson approximation" can be avoided to a large extent with more computation time. If, as some preliminary work suggests, collective degrees of freedom largely determine the matrix elements, then these methods, once they have been made to properly include all those degrees of freedom, should give results that are close to one another and to those of the shell model in nuclei where all the methods are applicable. They will certainly be in better agreement than they are now.

What about systematic effects, e.g. the "renormalization" of the axial-vector coupling g_A (that is, the consistent over-prediction of β and $2\nu\beta\beta$ matrix elements) that are not well understood in any framework? It is crucial to understand the degree to which whatever is responsible affects $0\nu\beta\beta$ decay. Here we can really expect rapid progress. Ab initio calculations and their extension via mapping to the shell model are able to include non-nucleonic degrees of freedom (through systematic many-body currents), short-range correlations, longer-range correlations that still escape today's phenomenological shell model, and valence-shell correlations. These not only all play at least some role in the suppression of g_A but also exhaust the possibilities. They can all be explored now in ^{48}Ca and other nuclei of similar or lighter mass. The suppression of β, $2\nu\beta\beta$, and $0\nu\beta\beta$ matrix elements can all be examined (even if the nuclei don't actually undergo $\beta\beta$ decay) and one will be able to see whether $0\nu\beta\beta$ decay is suppressed and if so by how much. Though it is not possible right now to conclusively eliminate a large g_A-related uncertainty in matrix elements, it will be within a few years.

Finally, the theory community is ready to do a serious correlation analysis with other observables, leading to a more quantifiable uncertainty; establishing the best framework will be one of the main goals of the upcoming NUCLEI collaboration meeting. More accurate calculations from a more organized and lager community of theorists are coming. It is hard to be precise about the time it will take and the level of accuracy that will be reached, but the uncertainty in the matrix elements should be considerably less than it is now by the time a ton-scale experiment is ready to take data.

E. US involvement in Current Searches for $0\nu\beta\beta$ Decay

The pursuit of $0\nu\beta\beta$ decay has led to the development of a broad suite of experiments, each with unique and complementary approaches. Analysis techniques may include both event-by-event rejection based on multiple discriminating variables, and multi-variate fits that extract signals from backgrounds based on the shapes of their respective distributions.

Two electrons with ∼MeV energies are emitted in double beta decay. For the neutrinoless decay mode the summed energy of the emitted electrons equals the well-known Q-value; good energy resolution is thus key for reducing the impact of background, and is especially important for minimizing the irreducible contribution from two-neutrino double-beta decay. The energy is deposited by electrons and not some other particle (highlighting the value of

particle ID), and is composed of two instead of just one electron, with simply-connected energy deposition (track topology). The spatial extent of events is much smaller than that expected for multiply-scattered energetic photons (single-site versus multi-site discrimination), and the large size and shielding of the detectors allows fiducial cuts to be made based on either position reconstruction or pulse shape analysis. The decay is neither preceded nor followed in time by correlated events (such as occurs in a ^{214}Bi-^{214}Po decay sequence), nor are candidate events correlated with cosmic rays or the delayed decay or interaction of their secondaries. Double beta decay produces a well-defined daughter nucleus, whose identification may be subject to tagging techniques. Information for fitting distributions of signals and backgrounds includes the shape of the energy sum peak, which is dominated by the detector resolution, or the uniform position distribution of candidate events as opposed to backgrounds like those from external sources that are biased towards the detector boundaries. The decay rate scales with the amount of deployed isotope, and the event time distribution is a constant rate, while backgrounds may have lifetimes shorter than the experimental running time. Lastly, the intrinsic rate of backgrounds, even before any analysis cuts, can be mitigated by improvements in purification techniques and in careful selection of materials.

The current generation of experiments on the 100-kg scale have been set up to explore this experimental parameter space and to help to eliminate many of the planning uncertainties. Finding the optimum approach is not easy as some input variables (e.g. the mix of background sources) are not known, and optimizing in one aspect may diminish another. For example, the instrumentation required to achieve additional analysis handles can come at the cost of increased background contributions and detector complexity. By construction, this is a competitive process, but it allows the development of the optimal approach on the fastest possible time scale and trains the US workforce eventually needed to build the next generation experiments. We list below the current generation of experiments with US involvement that have either produced results or are under construction, by their particular technique and where they are located:

- *Bolometry*: CUORE, which uses TeO_2 crystals and is at Gran Sasso (Italy).
- *Xe TPCs*: EXO-200 which uses liquid Xe, located at WIPP (New Mexico), and NEXT which uses high-pressure gaseous Xe and is located at Canfranc (Spain).
- *Germanium*: The MAJORANA Demonstrator which uses p-type point-contact germanium detectors and is located at Sanford Lab (South Dakota).
- *Loaded Liquid Scintillator*: KamLAND-Zen, which uses dissolved Xe and is located in Kamioka Mine (Japan), and SNO+ which uses Te loaded in linear-alkyl benzene and is located at SNOLAB (Canada).

We are in the fortunate position that results from each of these experiments over the next 1-2 years will answer the most critical questions regarding the efficacy of each approach.

In anticipation of the increase in experimental scale necessary to reach sensitivity to an effective Majorana neutrino mass of ∼15 meV, the DOE and NSF charged the Nuclear Science Advisory Committee (NSAC) to "form a Subcommittee to provide guidance to the DOE and NSF regarding an effective strategy for implementing a possible second generation U.S. experiment on neutrino-less double beta decay (NLDBD) [...]". Existing $0\nu\beta\beta$ collaborations were invited to present their current efforts and proposed future extensions to the Subcommittee. As part of their report, the Subcommittee summarized the characteristics of the "ideal" $0\nu\beta\beta$ experiment, and found that each of the approaches being pursued is typically strong in some of these characteristics, and weaker in others. The explicit details of each experiment's approach and how it aligns with the idealized experiment described by the Subcommittee, can be found in the Subcommittee's April 24, 2014 report.

The Subcommittee also directly addressed the scientific merit of neutrinoless double beta decay searches, stating "that the pursuit of neutrinoless double beta decay addresses urgent scientific questions of the highest importance, and that sufficiently sensitive second generation experiments would have excellent prospects for a major discovery. Furthermore, we recommend that DOE and NSF support this subject at a level appropriate to ensure a leadership position for the US in the next phase of discovery-caliber research." The Subcommittee made another important recommendation, that "[...] the current generation experiments continue to be supported and that the collaborations continue to work to resolve remaining R&D issues in preparation for consideration of a future second generation experiment. New techniques that offer promise for dramatic reductions in background levels should also be supported."

F. Tonne-scale Experiments and Timeline

The goal of discovery for the inverted hierarchy region translates into 3σ half life sensitivities ranging from 1.1×10^{27} yr to 3.5×10^{28} yr, depending on the nuclide and nuclear matrix element calculation used. Next-generation experiments must thus improve sensitivity by roughly two orders of magnitude over existing limits. The resulting

ultra-low decay rates per unit nuclide mass necessitate tonne-scale detectors to have measurable signal rates within a 10-year counting time.

It is clear to the $0\nu\beta\beta$ community that a decision will have to be made regarding the most promising technologies to work toward the tonne-scale. It is expected that following the decision the US community will come together to focus on the scientific goal, without regard to methodological approach. The NSAC Subcommittee provided criteria for this decision:

1. Discovery potential – 3σ sensitivity to effective Majorana masses of 15 meV, using the most conservative nuclear matrix elements.
2. Staging – Ability to approach maximum sensitivity/discovery potential by accumulating isotope mass and/or reducing background levels in stages that mitigate the investment risk.
3. Standard of proof – Capable of stand-alone, compelling independent evidence for a signal.
4. Continuing R&D – Pursue modest demonstrations that indicate the promise to dramatically enhance sensitivity, in parallel or in combination with ongoing searches.
5. International Collaboration – Develop international approach to $0\nu\beta\beta$ decay that would allow the investigation of multiple isotopes at the tonne scale.
6. Timeliness – A timescale competitive with that of international DBD efforts and of experiments aiming at pinning down the neutrino mass hierarchy.

The recommendation of 3σ sensitivity in the first criterion above deserves comment. It appears to fall short of the widely accepted 5σ criterion for major discoveries. However, the universality of that criterion is currently under much discussion within the high-energy physics community [72]. The 99.7% confidence level corresponding to 3σ is, indeed, inadequate in a broad search like that for the Higgs boson or other new particles of unknown mass because one must implicitly take into account a "trials" penalty due to the large number of possible bins being examined. The probability that at least one bin could fluctuate upward is much higher than that for any particular bin. In a much more narrowly focused $0\nu\beta\beta$ search, one knows *a priori* the precise energy at which a possible signal should appear, as well as the other observable features outlined in Section VI E that a real signal should exhibit. It would then be unnecessarily wasteful, with very substantial added cost and time, to aim for 5σ even in the pessimistic scenario where Majorana phases, nuclear matrix elements and neutrino mixing parameter uncertainties all conspire to make a $0\nu\beta\beta$ signal as small as possible for the exchange of light Majorana neutrinos with an inverted mass hierarchy. The NSAC Subcommittee thus felt that 3σ sensitivity in this "worst case" would optimize discovery potential within realistic cost and schedule guidelines. In order to minimize the possibility of confusion from an unidentified background source, it is desirable to have worldwide searches in at least two different isotopes. A 3σ signal near $< m_{\beta\beta} >= 15$ meV in one such experiment would be taken at the very least as important evidence and strong motivation for further pursuit. We believe that consistent 3σ signals in two experiments, or a signal from a sole experiment with $> 4\sigma$ significance at somewhat lower half-life, but meeting the "standard of proof" criterion above, would be nearly universally accepted as grounds for a discovery claim.

For each of the approaches listed in Section VI E, the respective collaborations are actively working on tonne-scale proposals that will address the NSAC Subcommittee's criteria. Below we list the proposals with US involvement examined by the NSAC Subcommittee. In some cases the efforts have different names or locations than those listed in Sec. VI E.

- *Bolometry (+Light)*: CUORE-IHE, based on the dual readout of heat and Cherenkov or scintillation light.
- *Xe TPCs*: nEXO which scales up EXO-200, and MAGIX which will scale up the NEXT approach.
- *Germanium*: MAJORANA+GERDA which would combine the two existing US and international germanium collaborations and increase detector scale.
- *Loaded Liquid Scintillator*: KamLAND-Zen, which will dissolve additional Xe and improve light collection, and SNO+ which will dissolve additional Te isotope with improvements in light yield.
- *Scintillator+Tracking*: SuperNEMO which uses a variety of isotopes in thin foils along with wire chamber tracking and plastic scintillator.

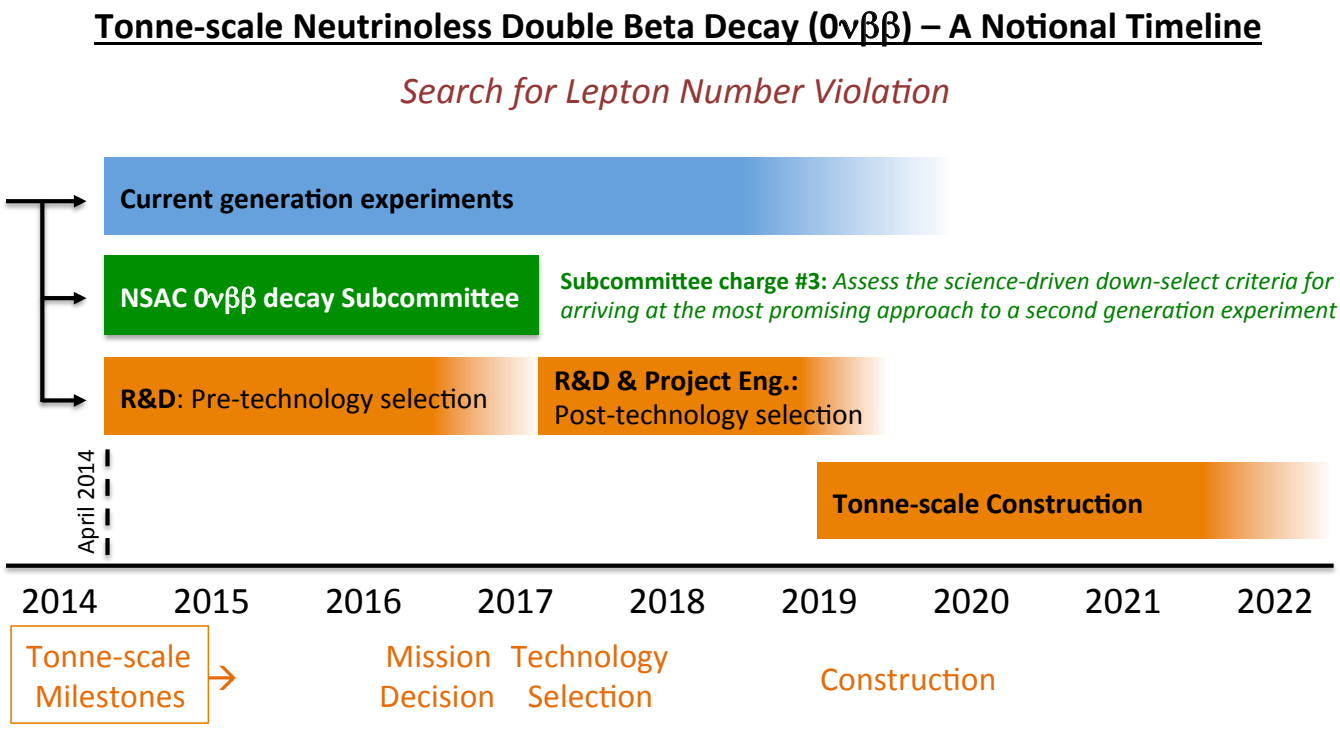

FIG. 2: Timeline for start of construction of a tonne-scale neutrinoless double beta decay experiment.

The Subcommittee also highlighted the need to proceed with technology decisions in a timely manner. In Figure 2 we show a notional timeline that gets the community from the existing suite of experiments to the start of construction of a tonne-scale experiment within the scale of this Long Range Plan. The timeline includes both the operation of existing experiments and the associated ongoing R&D, plus the necessary R&D needed to scale upward to the tonne scale.

The US has a highly trained scientific work force with the experience needed to take on and deliver a project of this size and complexity. US groups play leadership roles in many of the most promising projects. A broad experience base further exists in the form of groups that have worked on low energy rare event experiments not directly related to double beta decay (e.g. solar and reactor neutrino experiments), and cross fertilization is highly likely. Past investments, both in scientists and equipment, could therefore be leveraged against this new challenging goal. Maintaining this leadership role, however, does require a flagship project. A large next-generation double beta decay experiment led by the US would be such an "attractor." To ensure this, the down-select process must be set in motion within the next 2-3 years, as competing international efforts of similar scale are preparing to move forward on that time scale, and a discovery of major scientific impact is at stake. Without the start of construction of a tonne-scale experiment during the period covered by this Long Range Plan, not only will the US lose the opportunity to lead a project with Nobel-worthy discovery potential, but with the end of running of the existing experiments the critical knowledge base for building such experiments will begin to degrade, making a future experiment much less likely.

The expenditure and experimental effort needed to reach this sensitivity goal is justified by the important discovery potential it will provide. The investment remains worthwhile even if Nature conspires to violate lepton number conservation only at a level below that consistent with the inverted mass hierarchy. In that case, one would still have gained enormously in technical know-how on background reduction that will be essential for further pursuit of a violation whose scientific impact would still be too profound to ignore. Additional R&D would likely be needed to inform the choice of the optimal technical approach if Nature requires a further generation of experiments to go well beyond the tonne scale.

As a final point, reliance upon foreign suppliers for enriched material will be an important consideration for the path forward. Therefore re-establishing national isotopic enrichment capabilities would be directly beneficial to the broad US-based nuclear physics program.

System	Year/ref	Result
ThO	2014 [73]	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$ e-cm $C_S = (-1.3 \pm 3.0) \times 10^{-9}$
^{199}Hg	2009 [9]	$d_A = (0.49 \pm 1.5) \times 10^{-29}$ e-cm
neutron	2006 [74]	$d_n = (0.2 \pm 1.7) \times 10^{-26}$ e-cm

TABLE III: Limits on the EDMs of the electron (d_e) obtained from the ThO molecule, ^{199}Hg atom (d_A), and neutron d_n) as well as the T- and P-odd electron-scalar nucleon interaction C_S also obtained from ThO.

G. Conclusions

The goal of next-generation $0\nu\beta\beta$ experiments is discovery. The tonne scale will have sensitivity to lifetimes in the regime of 10^{27}–10^{28} years, two orders of magnitude or more beyond current-generation limits. Such sensitivity would not only discover $0\nu\beta\beta$ decay for m_1 as small as 50 meV, but has as a clear milestone coverage of the entire region corresponding to the "inverted hierarchy."

We feel that a timely start on a tonne-scale neutrinoless double beta decay experiment will provide a vital opportunity for the U.S. nuclear physics community to make a major scientific impact, with implications far beyond the field, and should be a very high priority of the upcoming Long Range Plan. The uniqueness of double beta decay to search for Majorana neutrinos, the technological advances in ultra-low background detection, and the theoretical machinery to improve matrix element calculations are all converging to point toward the tonne-scale goal. A large community of U.S. nuclear and particle physicists will coalesce around the challenge of reaching that goal with whichever experimental approaches emerge from a down-selection process within the next 2-3 years.

VII. SEARCH FOR ELECTRIC DIPOLE MOMENTS

A. Overview

Searches for the permanent electric dipole moments of the neutron and neutral atoms have a long and illustrious history in nuclear physics, providing one of the most powerful tests of time-reversal (T) and parity (P) invariance. Under the assumption of CPT invariance, these tests then probe CP invariance in the underlying interactions of leptons, quarks, and gauge bosons. Since the pioneering experiment by Ramsey and Purcell in the 1950's, the sensitivity of these searches has increased by several orders of magnitude. The null results obtained to date have now placed stringent upper bounds on the strength of CP-violation in the QCD sector of the Standard Model (SM), ruled out a variety of scenarios for CP-violation beyond the SM (BSM), and have severely constrained other BSM scenarios that include CP-violation at the TeV scale. The implications for both fundamental interactions and cosmology are far-reaching.

The three most stringent limits have been obtained for the ^{199}Hg atom, electron (inferred from an experiment on the ThO molecule), and neutron as indicated in Table III. Those for ^{199}Hg and the neutron imply that the coefficient of the CP-violating term in the QCD Lagrangian $\bar{\theta} \lesssim 10^{-10}$, assuming no other sources of CP-violation contribute[2]. This vanishingly small upper bound suggests the presence of a new symmetry of nature whose spontaneous breakdown would imply the existence of the axion, which remains a viable candidate for the observed abundance of cold dark matter. As discussed below, the limits obtained from ^{199}Hg, the neutron, and electron (inferred from ThO) imply a lower bound of several TeV on the mass scale associated with BSM CP-violation, while those from ThO imply that the mass scale associated with new electron quark interactions having maximal CP-violation is greater than ~ 1000 TeV. The bounds from all three systems have also squeezed the possibility that the minimal supersymmetric extension of the Standard Model is responsible for the cosmic matter-antimatter asymmetry into an LHC-inaccessible region of parameter space.

The next generation of EDM searches are poised to improve these sensitivities significantly, opening a path toward major discoveries. The search for a neutron EDM being developed for the Fundamental Neutron Physics Beamline (FNPB) at the Spallation Neutron Source would achieve a factor of ~ 100 improvement. Additionally an R&D effort

[2] The EDMs associated with CP-violation in the Cabibbo-Kobayashi-Masakawa matrix lie well below present and prospective future EDM search sensitivities.

currently underway at LANL, which includes an upgrade to the exsiting UCN source, could lead to a neutron EDM experiment with a factor of ~ 10 sensitivity improvement. A factor of ten improvement may be achievable for ^{199}Hg and ThO. New efforts are underway to search for the EDMs of ^{225}Ra, ^{129}Xe, $^{221/223}$Rn, and Fr, providing probes of BSM CP-violation complementary to those with the existing systems. Looking further down the road, storage ring searches for the EDMs of the proton and light nuclei involving U.S. nuclear physicists are under development in Korea and Europe and possibly at Fermilab. With these improvements, the mass scale reach of the next generation experiments could reach generically in to the ~ 50 TeV range, assuming maximal CP-violating phases, and conclusively test the possibility of the supersymmetric origin of matter in the minimal model. For recent reviews of the status and prospects for EDM searches and their theoretical interpretation, see, *e.g.* Refs. [75, 76].

The prospect for significant discovery with the next generation experiments builds on substantial experimental progress since the 2007 NSAC Long Range Plan and has also inspired significant theoretical advances.

The most important EDM results have been the new limit for ^{199}Hg [9], the neutron [74] as well as the order-of-magnitude improvement in the electron EDM from ThO[73]. Nuclear scientists are primarily involved in EDM studies of diamagnetic systems (i.e. with all electrons paired off such as for ^{199}Hg) which are chiefly sensitive to hadronic effects as well as the EDM of the free neutron and proton. For diamagnetic systems, based on the technical progress with the ^{199}Hg measurement, whose present limit is comparable to the neutron's limit in terms of basic physics reach, another factor of ten improvement in precision should be possible in the next five years, and an additional factor of five after 2020. Another promising avenue for diamagnetic atoms has appeared that takes advantage of an octupole enhancement of the EDM effect. In the US there is a promising experiment on ^{225}Ra that is underway that could produce exciting results by 2020. Significant progress also has been made in the R&D towards a proton storage-ring EDM measurement, while technical progress has been significant in developing a highly sensitive neutron EDM measurement. These last three efforts will be discussed below.

Theoretically, advances have been similarly substantial, including:

- Completion of new two-loop computations of EDMs and their analysis in a variety of BSM scenarios[77–80]
- Complete computation of the anomalous dimension matrix for the QCD evolution of dimension six CP-violating operators[81, 82] and calculations of higher order contributions to the nucleon EDMs relevant for left-right symmetric models [83]
- Development of a pion-nucleon effective field theory of T- and P-violating interactions, leading to a DNP Thesis Prize[45, 46]
- Computation of EDMs of light nuclei using the effective theory of P- and T-violating pion and nucleon interactions[84–86]
- Development of a framework for global analysis of EDM searches utilizing effective field theories at the pion-nucleon and elementary particle level[75, 76]
- Development of new, state-of-the art tools for computing the cosmic matter-antimatter asymmetry and their application to the confrontation of supersymmetric models with EDM limits[35–44]
- Development of new non-supersymmetric scenarios for weak scale generation of the matter-antimatter asymmetry compatible with present EDM constraints[87–89]
- Development of a framework to compute nucleon-level P-odd T-odd couplings induced by BSM operators within lattice QCD and Dyson-Schwinger approaches[90]. First results on nucleon EDM induced by quark EDM with all systematic uncertainties estimated.

Drawing on these theoretical developments, we first summarize the theoretical view of present and prospective EDM searches and their significance, followed by a discussion of the experimental opportunities.

B. Theoretical Landscape

1. BSM CP-violation, the Higgs Boson, and the complementarity of EDM searches

With the discovery of the Higgs-like scalar at the LHC, the possibility that it lies in an extended scalar sector has come to the fore. It is natural to ask, then, whether that sector violates CP and, if so, to what degree EDM searches might probe that CP-violation. One of the most widely studied such scenarios is the Two Higgs Doublet Model (2HDM). If realized in nature, it would imply the existence of four additional scalar particles (two neutral

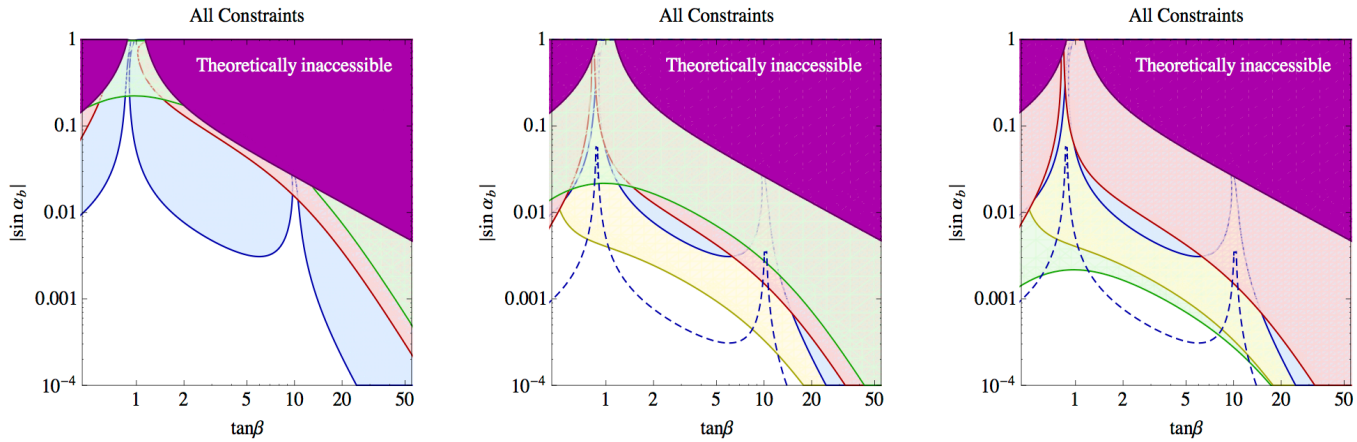

FIG. 3: Present and prospective EDM constraints on the type-II flavor conserving two Higgs doublet model as functions of $\tan\beta$ and the CP-violating phase α_b that characterizes CP-mixing in the Higgs sector[77]. Left panel gives presently excluded regions implied by null results for EDM searches on ThO (blue), ^{199}Hg (red), and the neutron (green). The purple region is disallowed by the constraints from electroweak symmetry breaking. Middle panel gives prospective reach assuming an order of magnitude improvement in sensitivity for all three systems (ThO indicated by dashed blue line), while the yellow region indicates prospective reach from the ^{225}Ra EDM search. The right panel indicates the future reach as in the middle panel but assuming an improvement of the neutron EDM sensitivity by two orders of magnitude.

and two charged) that could be discovered at the LHC and whose interactions generically include new CP-violation. The latter would be challenging to discern with collider experiments but would show up strongly in the EDMs of the electron, neutron, and diamagnetic atoms in a complementary way.

An illustration of this complementarity appears in Figure 3, taken from Ref. [77]. Shown are the present and prospective limits on the CP-violating phase α_b that, in this scenario characterizes mixing between CP-even and CP-odd scalars, as a function of $\tan\beta$, the ratio of of the vacuum expectation values of the two neutral, CP-even Higgs fields. The left most panel indicates the regions excluded by theoretical constraints (purple) and present limits from ThO (blue), neutron (green), and ^{199}Hg (red). The middle panel indicates the reach of next generation experiments assuming a factor of ten improvement in the present sensitivities (the ThO reach is indicated by the dashed blue line). The yellow region would be probed by the ^{225}Ra experiment presently being developed at Argonne National Laboratory. The right most panel gives the reach but assuming a factor of one hundred improvement in the neutron EDM sensitivity, corresponding to the goal of the nEDM experiment at the FNPB/SNS.

Several features emerge from these figures. First, the different systems provide complementary sensitivities. While the ThO experiment is clearly quite powerful, there exist regions near $\tan\beta = 1$ and $\tan\beta = 10$ where its sensitivity is significantly diminished, owing to cancellations among different contributions. The neutron and diamagnetic atom EDMs, on the other hand, can probe these regions for which ThO is insensitive. Second, the observation of a non-vanishing EDM in one system and the comparison with results from other systems could be used to determine the underlying model parameters. For example, a non vanishing result for both the neutron and ^{199}Hg, together with a vanishing result for ThO, would point to the region near $\tan\beta = 1$, while a non-vanishing result for all three would suggest one lies elsewhere. Finally, the next generation experiments may probe CP-violating phases in the 10^{-3} to 10^{-4} regime, a level of sensitivity that would be challenging at best for possible future CP-violation studies at a "Higgs factory" such as the International Linear Collider. These themes of powerful reach and complementarily apply to other BSM scenarios as well.

2. *Matter-antimatter asymmetry*

Explaining why the present universe contains more visible matter than antimatter is one of the key questions for nuclear physics. The imbalance is characterized by the baryon-to-entropy ratio, or baryon asymmetry of the universe (BAU)

$$Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11} \quad , \tag{2}$$

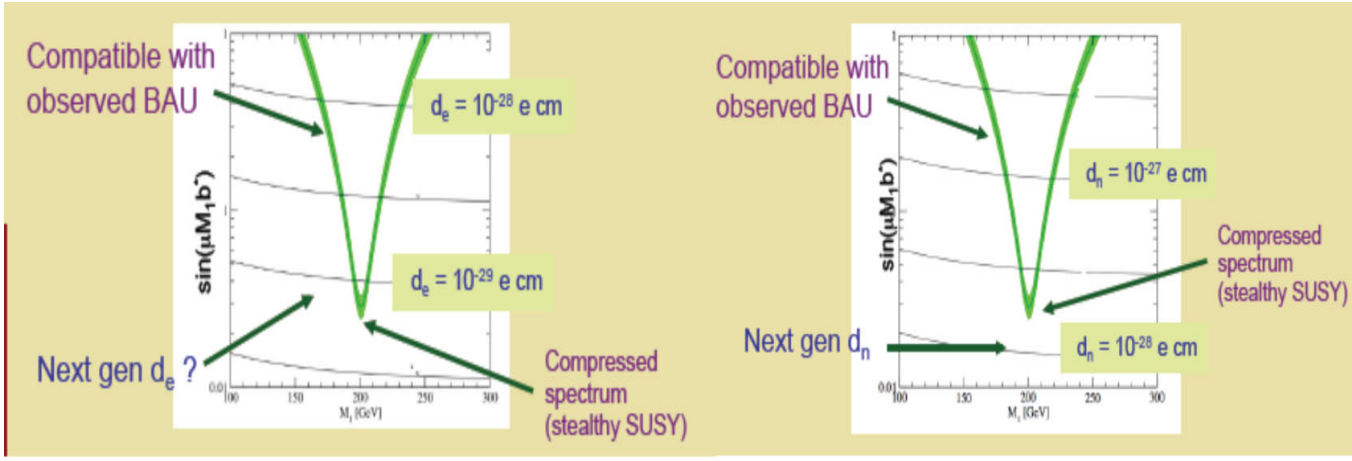

FIG. 4: EDM probes of baryogenesis-viable parameter space in the MSSM as functions of the "bino" mass parameter M_1 (horizontal axis) and related CP-violating phase $\sin(\mu M_1 b^*)$, assuming the supersymmetric mass parameter $\mu = 200GeV$. The green band indicates parameter regions consistent with observed baryon asymmetry and present theoretical BAU computations. Nearly horizontal lines give contours of constant EDM in the limit of heavy fermion super partners. Left panel indicates present and prospective electron EDM sensitivity, while the right panel shows prospective neutron EDM sensitivity. Figure adapted from adapted from Ref. [79].

where ρ_B is the baryon number density and s is the entropy density. Explaining why this ratio is not several orders of magnitude smaller requires the presence of BSM CPV in the early universe. With the observation of the Higgs boson whose properties are consistent with the SM paradigm of electroweak symmetry-breaking (EWSB), it is particularly timely to ask whether the BAU was produced during the EWSB era that occurred roughly 10 picoseconds after the Big Bang. If so, then EDM searches provide a particularly powerful probe of the associated CPV.

The most widely studied scenario for considering this questions it the minimal supersymmetric Standard Model (MSSM). Theoretical work completed since the 2007 NSAC Long Range Plan has sharpened the confrontation between MSSM "baryogenesis" and EDM searches[35, 36, 42, 44, 78–80]. Representative results are shown in Fig. 4, adapted from Ref. [79]. In each panel, the green band shows the region compatible with the observed baryon asymmetry as functions of the relevant CPV phase (vertical axis) and super symmetric particle mass parameter (horizontal axis). The nearly horizontal lines correspond to sensitivities of electron EDM (left panel) and neutron EDM (right panel) searches. The present ThO null result excludes the region above the line at 10^{-28} e cm . The reach of a future electron EDM search with ten times greater sensitivity would reach near the bottom of the supersymmetric baryogenesis viable parameter space, while an improvement in the neutron EDM search sensitivity by close to two orders of magnitude would have comparable reach.

The next generation experiments, thus, appear to be poised to provide conclusive tests of supersymmetric baryogenesis in the minimal model. Should either search obtain a non-vanishing result, one would then expect a corresponding signal in the other system if this scenario for generating the BAU is realized in nature. In short, searches for the EDMs of the neutron and paramagnetic systems with the planned sensitivities provide powerful, complementary diagnostic probes of one of the leading paradigms for explaining the matter-antimatter imbalance. It is also worth noting that direct observation of supersymmetric particles at the CERN Large Hadron Collider would be difficult, if not impossible, to achieve for regions of model parameter space near the bottom of the green funneled region. Should nature have chosen this region, EDM searches may be one of the only means of accessing this scenario, albeit indirectly.

3. EDM searches and the BSM mass scale: model independent implications

While it is certainly interesting to analyze EDM implications within specific BSM scenarios, one may also derive significant insight utilizing a model-independent, effective field theory (EFT) approach. Going beyond the SM, the leading EFT interactions involving elementary particles that may generate a non-vanishing EDM occur at mass dimension six, implying that they carry two inverse powers of the BSM mass scale Λ. One may then map these interactions onto hadronic and nuclear degrees of freedom by exploiting the associated chiral and isospin transformation properties. The development of the EFT framework for performing this matching constituted a portion of the work of the Ph.D. thesis of Emanuele Mereghetti that was awarded the 2012 Dissertation Award in Nuclear Physics.

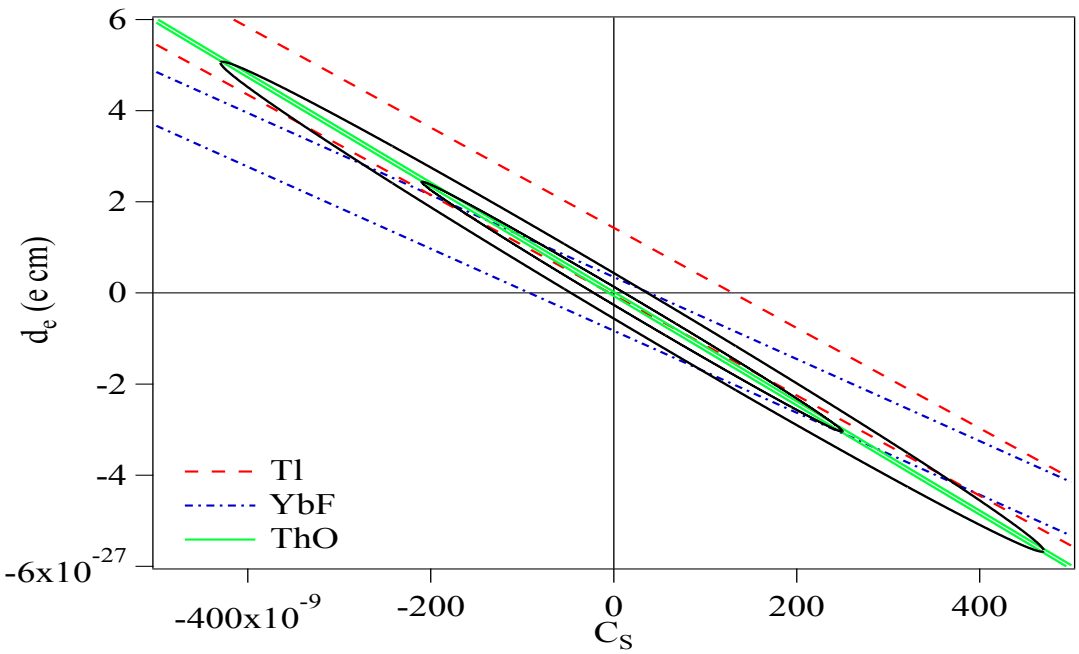

FIG. 5: Model-independent constraints on electron EDM d_e and coefficient C_S of pseudoscalar electron × scalar quark CP-violating interaction obtained from null results for ThO, YbF, and Tl EDM searches[75].

The underlying EFT's at the elementary particle and hadronic level have subsequently been applied to the analysis of present and prospective EDM searches to derive lower bounds on the mass scale Λ and to analyze the theoretical hadronic uncertainties in EDM computations (see below). Representative results are indicated in Fig. 5 [75], where one sees the sensitivity of paramagnetic EDM searches to the electron EDM (vertical axis) and coherent electron-quark CPV interaction (horizontal axis). When translated into mass scale reach, one obtains[75]

$$\Lambda \gtrsim (1.5 \text{ TeV}) \times \sqrt{\sin\phi_{\rm CPV}} \qquad \text{Electron EDM (global)} \tag{3}$$

$$\Lambda \gtrsim (1300 \text{ TeV}) \times \sqrt{\sin\phi_{\rm CPV}} \qquad C_S \text{ (global)} \tag{4}$$

In the purely hadronic sector relevant to the neutron and diamagnetic atom EDMs, the CPV quark-gluon interaction, or quark "chromo-EDM" (CEDM), may give rise to long-range a T- and P-violating NN interaction mediated by pion exchange. A global analysis of the corresponding diamagnetic atom and neutron results constrains this long-range interaction, leading to the lower bound on Λ from the CEDM:

$$\Lambda \gtrsim (2 \text{ TeV}) \times \sqrt{\sin\phi_{\rm CPV}} \qquad \text{Isoscalar quark chromo} - \text{EDM (global)} \quad . \tag{5}$$

These statements of mass reach are significant . First, assuming CPV of maximal strength, one has lower bounds of a few TeV for the dipole interactions to well over 1000 TeV for the coherent electron-quark interaction. The former mass range is presently within reach of the LHC, but a factor of ten improvement in sensitivity would push into territory beyond the LHC reach. For the coherent electron-quark interaction, the mass reach lies well beyond the realm of both the LHC and any currently envisioned high-energy colliders. Note that a factor ~ 100 improvement in the neutron EDM sensitivity would extend the sensitivity to the 10-50 TeV range, again well beyond what may be accessible with future high-energy facilities. We note that a future experiment in a system having different sensitivities to d_e and the electron-quark interaction C_S could be particularly advantageous in probing these two interactions if performed with sufficient sensitivity. One possibility under active study is to search for the EDM of francium.

4. Theoretical challenges

The theoretical progress since the 2007 NSAC Long Range Plan has significantly advanced the interpretation of EDM searches in terms of underlying fundamental interactions and the broader implications for the origin of the

matter-antimatter asymmetry. Nevertheless, considerable challenges remain that call for the deeper engagement of nuclear theorists with expertise hadronic and many-body physics. In particular, the computation of hadronic parameters, such as the neutron EDM or the P- and T-violating pion-nucleon couplings, presently entail significant strong-interaction uncertainties. Depending on the underlying dimension-six interaction, these uncertainties may be as large as one order of magnitude[76]. Looking to the next decade, the application of *first principles* computations using lattice QCD and Dyson Schwinger equations hold the promise of significantly improving the reliability of these computations and achieving smaller theoretical uncertainties.

A similarly important challenge applies to nuclear many-body theory. The EDMs of diamagnetic molecules, ^{199}Hg, ^{225}Ra, ^{129}Xe, and$^{221/223}$Rn are generated by the so-called nuclear Schiff moment, effectively an r^3-weighted moment of the P- and T-violating nuclear charge operator. As with the hadronic matrix elements, the nuclear Schiff moments remain subject to considerable theoretical uncertainties[76], particularly in the case of ^{199}Hg. More theoretically robust computations appear possible in the octupole-deformed systems, such as ^{225}Ra, where the Schiff moment is dominated by mixing between nearly-degenerate, opposite parity states.

In both cases, investment of additional resources in theoretical computations will be a vital component of a longer-term program to theoretically interpret the results of EDM searches, complementing the on-going efforts to refine state-of-the-art efforts in computing the BAU and to compute the dimension six CPV interactions in various BSM scenarios.

C. Experimental Landscape

As discussed above, the discovery of a neutron EDM (Electric Dipole Moment) above the Standard Model background, which lies more than five orders of magnitude below the present limits, would be first evidence for a new type of time-reversal violation and CP violation. Since the specific physics origin of an EDM can lead to an observable EDM in one system (e.g. hadronic systems) while being unobservable for other systems (e.g. leptons), it is important to search broadly. There is also a risk of false positives *and* negatives, so an EDM limit set by a single experiment should not be relied upon to favor one model over another: confirming experiments are needed, particularly for the atomic and molecular systems. Consequently, a wider program of EDM experiments should be supported at both the prototype and full scale level. Learning lessons from the neutron EDM community, more interaction between EDM experimenters across different experiment would be beneficial, as would coordinated or shared research & development.

A number of EDM experiments are funded or are seeking funding from the DOE and NSF Nuclear Physics programs. These include a number of efforts in on-going off-shore experiments (the ^{223}Rn atomic EDM experiment at TRIUMF in Vancouver and the neutron EDM experiment at the FRMII reactor in Munich). There are also a number of efforts in the US. The ^{199}Hg experiment at the University of Washington has reported a sensitive limit for an hadronic EDM[9]. Future support for this experiment is needed to allow the effort to achieve its maximum sensitivity. Other experiments are in the development stage including the ^{225}Ra experiment at Argonne National Laboratory, a storage ring proton EDM experiment, and several neutron EDM experiments. These will be described below.

1. *Octupole enhanced EDM of ^{225}Ra*

The diamagnetic atom ^{225}Ra ($\tau_{1/2} = 14.7$ d, $I = 1/2$) is mostly sensitive to T- and P-violating effective interactions between nucleons within its nucleus. As discussed above, the best limits on these types of interactions are derived from the 2009 atomic EDM limit for ^{199}Hg by the Washington-Seattle group. Because of its nuclear octupole deformaton ("pear" shape) and the unusually small splitting of its lowest lying parity doublet (55 keV), ^{225}Ra is expected to have a physics sensitivity that is a few hundred to a few thousand times higher than ^{199}Hg. Laser cooling & trapping techniques are performed offline to collect & transport the Ra atoms into the measurement region [91, 92]. An EDM search using cold atoms tighly confined in an optical dipole trap is less sensitive to geometric phase effects, relaxes requirements for magnetic field uniformity, and allows for the application of a higher electric fields. The measurement is performed by searching for a linear electric-field dependent shift in the nuclear spin precession frequency of ^{225}Ra. In October 2014, the spin precession of ^{225}Ra in electric and magnetic fields was observed for the first time. A schematic of the apparatus used in the measurement is shown in Fig. 4.

The initial goal is to perform an EDM measurement which would provide physics reach that is already competitive with the 2009 ^{199}Hg result. The eventual goal is to perform a measurement with a physics reach at least an order of magnitude beyond ^{199}Hg. In order to achieve this goal, a more intense and reliable source of ^{225}Ra will likely be needed to increase both the number of atoms and the integration time, as well as to allow for detailed studies of systematics. This could be provided by harvesting the ^{225}Ra expected to be produced at the Facility for Rare Isotopes

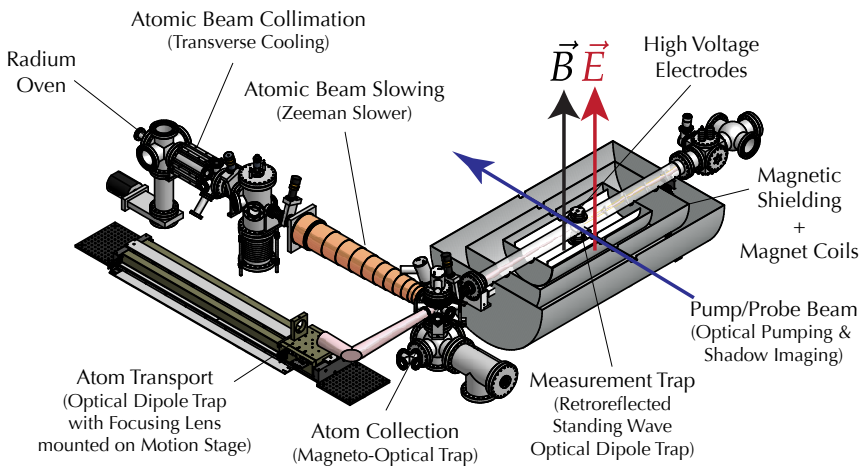

FIG. 6: Experimental Layout for Radium EDM.

Beams, presently under construction. In order to take advantage of this possibility at FRIB, it is critical to support a dedicated program to develop the expertise and infrastructure needed to harvest ^{225}Ra.

2. *Storage ring measurement of proton EDM*

An intriguing concept is under development to store polarized protons in an all-electric field storage ring in order to measure the proton EDM. The concept is to store protons at the "magic" momentum of 0.7 Gev/c where the spin of the proton, initially pointing along the momentum vector, will continue to point along the momentum in the absence of an EDM. For a non-zero EDM, the horizontal E-field of the ring will cause the spin vector to develop a vertical component which can be detected with a spin analyzing scattering reaction. Due to advancements in accelerator technology, a high current of protons can be stored providing ample statistical sensitivity all the way down to 1×10^{-29} e-cm. Active R&D is underway to develop techniques to achieve a similar systematic sensitivity. Such a ring has been discussed for both BNL and Fermilab. Some nuclear physics funding may well be sought for such an effort, as this type of sensitivity (ten times better than the proposed next generation neutron EDM experiments) would probe even higher mass scales for BSM physics.

3. *New experiments on neutron EDM*

Regarding the neutron EDM, experiments have searched for such an observable for over six decades, during which time the sensitivity has improved by nearly eight orders of magnitude. Failure to observe a non-zero EDM has severely constrained many different versions of beyond-Standard-Model physics, including minimal supersymmetry (e.g. MSSM).

For the neutron, eight experiments worldwide have begun, at least one of which should produce an improvement in sensitivity by a factor of five in the next several years. Beyond that, several experiments (including the SNS nEDM experiment) are being developed to improve the sensitivity by a factor of 100. The experiments with the highest sensitivity and their estimated reach are summarized in Table II. The number of worldwide efforts to measure the neutron EDM illustrates the excitement in the scientific community to determine this important quantity.

In the US there are two projects underway to improve the sensitivity to a neutron EDM one at Los Alamos National Laboratory (LANL) and the other at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. LANL currently operates a proton-beam-driven solid-deuterium-based UCN source [93], providing UCN for for various experiments including the UCNA, UCNB, and UCNτ experiments. The LANL UCN source is one of the few operating UCN sources in the world and is the only one in North America.

The density of unpolarized UCN currently obtainable at the exit from the biological shield of the LANL UCN source is ~ 50 UCN/cc [93]. An estimate, based on calculations and measurements, shows that the combination of further optimization of the source geometry and cold moderator material, increased proton beam current, and more optimized proton pulse structure will provide a 10-fold increase in UCN source performance. With such an improvement, an nEDM experiment with a sensitivity goal of several $\times 10^{-27}$ e·cm based on the already proven Ramsey's separated

Experiment	UCN Source	Cell	Measurement Technique	σ_d (10^{-28} e·cm)
PNPI (ILL)	ILL turbine PNPI/Solid D_2	Vacuum	Ramsey technique for ω $\vec{E}=0$ cell for magnetometer	Phase 1 < 100 Phase 2 < 10
PSI EDM	Solid D_2	Vacuum	Ramsey technique for ω External Cs and $^3\vec{\mathrm{He}}$ magnetometers Possible Hg or Xe comagnetometer	Phase 1 $\approx$ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vacuum	Under construction Similar to PSI EDM	< 5
nEDM (SNS)	Superfluid ^{4}He	^{4}He	^{3}He capture for ω ^{3}He comagnetometer SQUIDS & Dressed spins	< 5
Osaka/TRIUMF	Superfluid ^{4}He	Vacuum	Phase I + Phase II	< 5
JPARC	Solid D_2	Vacuum	Under development	< 5

TABLE IV: Summary of worldwide nEDM searches with sensitivity goals below 1×10^{-27} e-cm.

oscillatory fields method at room temperature could be performed at the LANL UCN source. Note that, although there are currently many efforts world-wide (see above) to improve the sensitivity for the neutron EDM, all of the advanced efforts are, at the minimum, held up by lack of a sufficient UCN density. Note also that some of these efforts have made significant technological advancements, including the attainment of a uniform and stable magnetic field [94], necessary to keep certain systematic effects sufficiently low for next generation nEDM experiments.

Currently, a LANL internally funded effort (FY14-16) is under way to improve the UCN source and demonstrate a density of stored UCN sufficient for an nEDM experiment in a prototype nEDM apparatus. If successful, the improved source at LANL could provide a venue for the US nEDM community to perform an nEDM experiment and obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the technically challenging SNS nEDM experiment continues. The cost necessary to complete the construction of the experiment after the current LANL internal funding is estimated to be approximately $5M, a large fraction of it being for magnetic shielding. With foreign collaborators with existing apparatus joining the effort, the cost would be substantially lower.

The goal of the SNS nEDM experiment is to achieve a sensitivity $< 5 \times 10^{-28}$ e-cm. A conceptual design of the experiment is shown in Fig. 5. A value (or limit) for the neutron EDM will be extracted from the difference between neutron spin precession frequencies for parallel and anti-parallel magnetic ($\sim$ 30 mGauss) and electric ($\sim$ 75 kV/cm) fields. This experiment, based on Ref. [95], uses a novel polarized ^{3}He co-magnetometer and will detect the neutron precession via the spin-dependent neutron capture on ^{3}He. A high density of trapped ultra-cold neutrons is produced via phonon production in superfluid ^{4}He which can also support large electric fields.

The experiment has several characteristics that distinguish it from the others being planned. These characteristics typically reduce potential systematic effects, and/or allow a better understanding of them. These characteristics include:

- directly loading the neutron trap with UCNs that are produced in $\sim$ 0.4 K liquid He via the phonon recoil process [96]
- using superfluid ^{4}He as a working medium to allow for very high electric fields
- using a dilute mixture of polarized ^{3}He in superfluid ^{4}He as a co-magnetometer. This works due to electron screening of the ^{3}He nucleus resulting in a negligible atomic EDM for ^{3}He.
- using a sensitive SQUID measurement of the precession frequency of the ^{3}He magnetic dipoles
- using a superconducting shield to isolate the measurement region from external magnetic field fluctuations
- determining the difference in the neutron and ^{3}He precession frequencies from the spin-dependent absorption cross section and the subsequent variations in light intensity from scintillations in the ^{4}He
- allowing for two techniques for measuring the EDM: the free precession method with SQUIDs or a dressed-spin method that uses a high-frequency magnetic field to modify the effective magnetic moments of the two polarized species [95]
- using the temperature dependence of the geometric-phase false EDM effect[97–99] for ^{3}He to characterize this important systematic effect.

The 2011 NSAC Fundamental Neutron Physics Panel was strongly supportive of the physics goals of the SNS experiment, but was concerned about some remaining technical hurdles. The report [100] reiterated the scientific motivation for EDM searches, saying they remain as compelling as ever. This report stated that "... a measurement

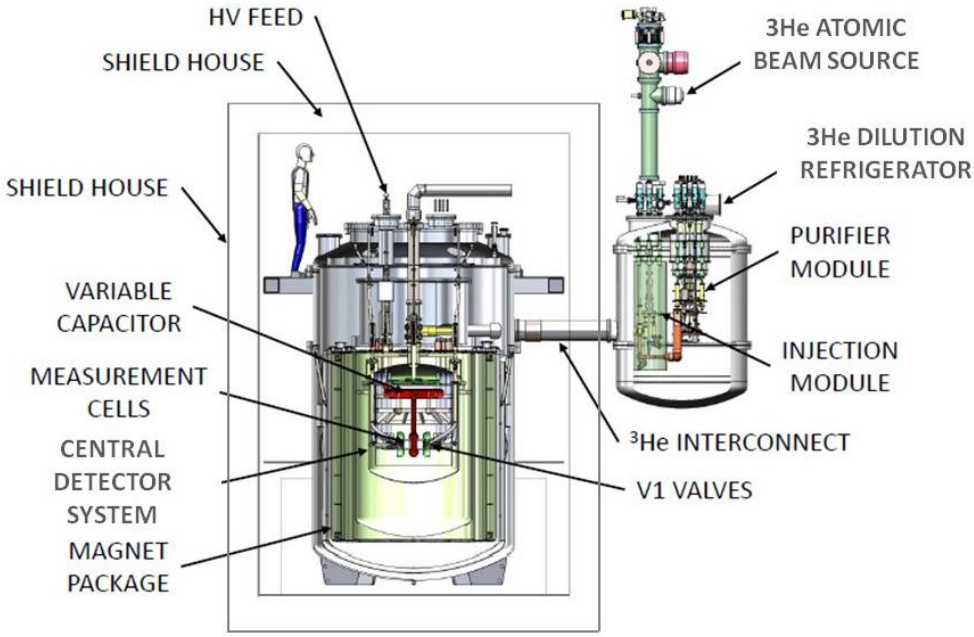

FIG. 7: Schematic diagram of the SNS nEDM apparatus. The neutron beam trajectory is into the page

with sensitivity at the anticipated reach of the US nEDM experiment ($\sim 4 \times 10^{-28}$ e-cm) would have a profound impact on nuclear physics, particle physics and cosmology even in the event of a negative result." The committee deemed this to be the initiative with the highest scientific priority in US neutron science [100]. In their words, "A non-zero EDM would constitute a truly revolutionary discovery." The report also outlined a series of technical concerns including demonstration of high electric fields in low temperature liquid He, sufficiently uniform magnetic fields, sufficient photo-electron yield and capability of ^{3}He transport. A two-year Critical R&D phase was begun where each of these technical concerns were actively addressed. In 2013 a joint NSF/DOE review of the project concluded that the main technical goals outlined by the previous Panel had been achieved and that the collaboration should begin building the most technically challenging components of the experiments (discused below).

Control of systematic errors is essential for an experiment at the 10^{-28} e·cm level. The different collaborations have chosen different approaches, but the SNS nEDM experiment has the most extensive program for controlling and estimating systematic errors. A list of techniques incorporated into the designs of the experimental approaches is shown in Table III.

Capability	**FRM**	**PSI1**	**PSI2**	**SNS**
$\Delta\omega$ via accumulated phase in n polarization	Y	Y	Y	N
$\Delta\omega$ via light oscillation in ^{3}He capture	N	N	N	Y
Horizontal B-field	N	N	N	Y
*Comagnetometer	Y	Y	Y	Y
*Superconducting B-shield	N	N	N	Y
*Dressed Spin Technique	N	N	N	Y
*Multiple EDM cells	Y	N	Y	Y
*Temperature Dependence of Geometric phase effect	N	N	N	Y

TABLE V: Comparison of capabilities for nEDM searches. The last five items marked with an * denote a systematics advantage.

The SNS nEDM experiment represents a major technical challenge and requires a team with broad technical knowledge and extensive experience. The collaboration includes researchers from twenty institutions with expertise in nuclear, atomic, and low-temperature physics. They have made significant progress in addressing important technical issues with a number of significant accomplishments. Recently the funding agencies endorsed the collaboration's plan to begin a new phase of the experiment called Critical Component Demonstration (CCD) wherein the most technically challenging aspects of the experiment will be developed to a sufficient level of technical readiness to allow completion

of the more conventional experimental components (such as neutron beam line, external magnetic shielding and local infrastructure). Key issues being addressed during the CCD phase include:

1. Maximum electric field strength for electrodes made of appropriate materials in superfluid helium below a temperature of 1 K.
2. Magnetic field uniformity for a full-scale magnetic coil and a Pb superconducting magnetic shield.
3. Demonstration of sufficient photoelecton yield from the scintillation in superfluid helium.
4. Development of coated measurement cells that preserve neutron and ^{3}He polarization along with long neutron storage times.
5. Understanding of polarized ^{3}He injection and transport in the superfluid ^{4}He.
6. Exploring the systematics of the dressed spin technique including polarized UCN and ^{3}He.

The experiment will be carried out on the Fundamental Neutron Physics Beamline (FNPB) at Oak Ridge National Laboratory's Spallation Neutron Source (SNS). Additional funds to complete the experiment are estimated to be $\sim$ \$40M. Construction is likely to take at least five years, followed by hardware commissioning and data taking by the end of the decade.

VIII. LEPTON PROPERTIES AND INTERACTIONS

A. Introduction

Precision studies of the properties of the leptons – both charged and neutral – are among the most powerful probes of phenomena that transcend our current understanding of fundamental interactions.

The last twenty years have revealed beyond reasonable doubt that neutrinos have mass and that leptons mix. Detailed understanding of neutrino interactions with nuclei is mandatory if the next generation of long-baseline neutrino oscillation experiments is to reach all its goals, including testing leptonic CP invariance. Such understanding calls for a comprehensive program to precisely describe neutrino scattering. A case in point is the long-baseline neutrino experiment LBNE being initiated in high energy physics; the success of such a project in extracting the best possible information will depend on detailed input from nuclear theory and measurements of neutrino cross sections.

Precision studies of neutrino scattering at low energies are also necessary in order to fully exploit the neutrino data from the next galactic supernova explosion. At the same time, very low-energy neutrino scattering provides a unique probe of certain manifestations of new physics.

The understanding of neutrino properties also requires experimental activities outside of accelerator-based neutrino oscillation experiments. A high-statistics measurement of the atmospheric neutrino spectra might prove to be a powerful tool for revealing the neutrino mass hierarchy, as described in detail in Section X "New Initiatives." On a very different front, precision measurements of the β-ray energy spectrum in β-decay provides the only earth-bound laboratory probe capable of observing direct effects of nonzero neutrino masses that are independent of the nature – Majorana or Dirac – of the neutrinos.

Precision studies of electron scattering remain among the most powerful probes of new phenomena, and provide unique measurements of standard model parameters, including the weak mixing angle. Precision studies of muon properties continue to inform the weak interactions via the muon lifetime and Michel parameters. The measurement of the anomalous magnetic moment of the muon remains the strongest hint for new physics at the weak scale (100 GeV), while searches for muon-number violation – $\mu \to e\gamma$, $\mu \to e$-conversion in nuclei, etc – provide some of the most stringent bounds on new phenomena at (and well above) the weak scale.

B. Neutral Leptons – Neutrino Masses from Kinematics

Neutrino masses –or, more specifically, the absolute *scale* of neutrino masses– remains one of the more intriguing and difficult problems to tackle in experimental neutrino physics. Understanding the neutrino mass scale has vast implications for both theoretical models hoping to understand the nature and structure of masses, as well as the impact neutrinos can have on cosmology. To date, radioactive decay appears to be the most direct, model-independent approach for measuring the mass scale of neutrinos. Decay kinematics suffer neither from the inherent dependence on cosmological models, nor on the property of neutrinos necessarily being their own anti-particles. As such, this

kinematic approach toward neutrino masses can be placed in direct comparison with the predictions from neutrino oscillations. Deviations from the prediction, for example via the existence of sterile neutrinos, can also be readily tested.

TABLE VI: Impact of neutrino mass sensitivity level as obtained from beta decay measurements on nuclear physics and cosmology.

Mass Sensitivity	Scale	Impact
$m_\nu \sim 2$ eV (current sensitivity)	eV	Neutrinos ruled out as primary dark matter
$m_\nu \sim 0.2$ eV	Degeneracy	Cosmology, $0\nu\beta\beta$ reach
$m_\nu \sim 0.05$ eV	Inverted	Resolve hierarchy if null result
$m_\nu \sim 0.01$ eV	Normal	Oscillation limit

The leading experiment for direct neutrino mass searches is the KArlsruhe TRItium Neutrino mass experiment (KATRIN) [101, 102], nearing completion with strong U.S. participation. KATRIN uses the technique of magnetic adiabatic collimation with electrostatic filtering (MAC-E filter) to achieve exquisite energy resolution and high luminosity [103–105]. Commissioning studies have already demonstrated better than 1 eV precision on the electron kinetic energy. KATRIN is scheduled to begin taking data using gaseous tritium in 2017. A 5 calendar year (3 year livetime) measurement would yield a neutrino mass limit of better than 0.2 eV at 90% C.L. (or a 5 σ discovery for a neutrino mass scale of 0.35 eV).

Further improvement on the MAC-E Filter technique appears unlikely due to the requirements imposed by both the energy resolution and high activity which drive the experiment to extremely large volumes. Fortunately, new techniques are currently being pursued. Low temperature micro-calorimetry offers a complementary approach for measuring the neutrino mass scale. In a perfect calorimeter, the energy released from the decay –except for the neutrino energy– is fully absorbed. As such, the detector and the source are no longer distinct, and the detector becomes relatively insensitive to the details of the final state interaction or energy loss mechanism. Such a technique provides a distinct approach to that of MAC-E Filters. The calorimetric approach is an outgrowth of the original studies done by the MARE experiment using the forbidden β decay of ^{187}Re [106]. More recent efforts have focused on the allowed electron-capture decay of ^{163}Ho [107]. Such efforts are underway in Germany (ECHO), Italy (HOLMES), and the US (NuMECS). A broad program that focuses on detector R&D and understanding of various systematics is currently ongoing.

In addition, a new frequency-based technique which uses cyclotron radiation emission spectroscopy has also been proposed to precisely measure the energy of electrons from radioactive gaseous sources such as tritium [11]. The US effort (Project 8) has recently demonstrated the proof-of-principle of the technique by measuring the cyclotron emission from single electrons emitted from the decay of ^{83m}Kr. The frequency-based method has potential in overcoming some of the limitations present in current techniques, and projections indicate that reaching the inverted scale (by switching to atomic tritium rather than molecular tritium) appears feasible [108]. Reaching the inverted mass scale ($\sim$ 50 meV) with direct neutrino measurements has significant consequences for the field, as it will be able to address questions about the neutrino mass hierarchy and allow more direct comparisons with cosmological measurements.

C. Neutral Leptons – Neutrino–Nucleus Interactions

The neutrino has shown itself to be a complicated particle having mass and with flavor states composed of an oscillating mixture of mass eigenstates. In the United States, significant investment is being made to further investigate this profound behavior of the neutrino. In particular, our sights are set on precisely testing the current 3-neutrino mixing picture, determining the mass hierarchy and whether or not neutrinos violate CP, the latter of which can only be tested with accelerator-based sources of neutrinos. In accelerator-based neutrino oscillation experiments, the goal is to measure the appearance and/or disappearance of a given neutrino flavor as a function of the incident neutrino energy. The signal for appearance or disappearance can be the observation of an exclusive process or inclusive production of a particular neutrino flavor in the detector. In both cases, the neutrino is interacting with a complex nucleus since all present and planned long baseline experiments use nuclear targets (^{12}C, ^{40}Ar, ^{56}Fe,..).

Neutrino scattering at the energy range relevant for long-baseline oscillation experiments, from a few hundred MeV up to tens of GeV, is fraught with theoretical uncertainties, and existing data are sparse and have large errors.

Furthermore, extracting the neutrino properties from the data requires knowledge of the incoming neutrino energy which is - unlike in any other nuclear physics experiment - a priori not known and must be reconstructed from the final state of a neutrino-nucleus reaction on an event-by-event basis. This requires a quantitative understanding of the reaction mechanism, including the final state interactions, which has to go well beyond the calculation of inclusive cross sections [109].

A clear example of this problem and of the synergy of nuclear theory and neutrino physics has emerged in connection with recent quasielastic scattering measurements on nuclear targets performed by the MiniBooNE experiment. Only very recently, calculations have shown that a significant portion of the weak response of a nucleus is due to two-body terms [110, 111]. Only after taking into account these two-nucleon mechanisms (two-particle-two-hole excitations) has it been possible to reconcile these experimental results with the limited information on the nucleon axial form-factor available from neutrino scattering on deuterium and pion electroproduction. These two-particle-two-hole excitation mechanisms also help describe the dip region between the quasi-elastic and $\Delta(1232)$ peaks observed in electron scattering. These findings have important implications for neutrino-oscillation experiments as a source of systematic error in the determination of the neutrino energy, which is not known for the non-monochromatic neutrino beams [112]. The primary distributions from such 2p-2h processes will be heavily distorted by final state interactions and, therefore, model discrimination would require a high precision and considerable improvements in the understanding and simulation of such reactions.

Indeed, more so than in any other nuclear physics experiment - with the possible exception of ultrarelativistic heavy-ion collisions - neutrino long-baseline experiments necessarily require the use of neutrino generators, i.e., nuclear physics based descriptions of the full final state of the neutrino-nucleus reaction, in order to extract the relevant physics from the raw data. The precision with which neutrino properties can be extracted from long-baseline experiment is clearly affected (and limited) by the quality of the generator used. 'Quality' here applies both to the physics content as well as to the numerical implementation. Since all modern and planned long-baseline neutrino experiments use nuclear targets, it is important to realize that a relevant fraction of the final-state particles are produced in secondary collisions in the nuclear medium. The need for a theoretical framework and generator, that incorporates our present knowledge of interactions of leptons with nucleons and nuclei, is then obvious.

A particularly interesting example of the impact of nuclear effects on neutrino energy reconstruction can be illustrated with the sensitivity of the oscillation signal to the presence of a non-vanishing CP-violating phase δ_{CP}. This is shown in Fig. 8 for the two extreme cases $\delta_{CP} = \pm\pi/2$; here the neutrino flux expected for LBNE has been used. For such a measurement, a subset of 0 pion events is experimentally often chosen to suppress the pion production events which constitute a major background at LBNE energies. For $\delta_{CP} = -\pi/2$ the minimum at around 1.5 GeV has nearly completely disappeared in the distribution of reconstructed energy for these 0 pion events in the upper part of Fig. 8; the differences between the event distributions for true and reconstructed energy are particularly large to the left of the main peak. However, the further restriction of the event sample to 0 pion, 1 proton and X neutrons changes this picture dramatically (see lower part of Fig. 8). Now again the true and reconstructed curves have a very similar structure with a shift of only about 100 MeV. The accuracy of the energy reconstruction has thus significantly been improved by a proper choice of events. The results shown in Fig. 8 were obtained by using nuclear transport theory, that has proven its value in other branches of nuclear physics [114], to model neutrino interactions in argon.

The neutrino generators usually used by experiments have grown historically into a collection of, often undocumented, physics recipes and still contain outdated physics modeling. Furthermore, they are mostly black boxes and are not on the same state-of-the-art as the nuclear equipment for neutrino experiments is. It should, furthermore, be noted that there are several different event generators in use that would give different reconstructed distributions and the challenge to the nuclear physics community is to help determine which of these is the superior model. A demanding task standing ahead is thus to integrate the new methods of nuclear theory and our present knowledge of electron-nucleus interactions in a consistent framework that is flexible and fast enough to meet the needs of experimental analyses. The development of a state-of-the-art neutrino generator that allows for easy ongoing maintenance and improvements and that is well documented must be an integral part of any major new experiment as important as LBNE. At the same time, experiments such as MINOS+, MicroBooNE, MINERvA (with CAPTAIN) and NOVA, but also at JLAB with electrons, could provide data for ongoing tests of our understanding of neutrino-nucleus interactions.

The time, about 6 - 9 years before the start of LBNF, is just right to start to build a scientific community around the question of neutrino-nucleus interactions. The recently formed Neutrino Scattering Theory Experiment Collaboration (NuSTEC) initiative [115] is a first promising step into this direction. Such a program would require a dedicated nuclear theory support for studies of lepton-nucleon and lepton-nuclear reactions, with close contact to a strong experimental program at Fermilab and at JLAB; in addition, expertise from numerically intensive computing would be extremely helpful. Such a research program, being localized on the experimental side in high energy physics and on the theoretical side in nuclear theory, also requires a new approach to uniting DOE-based high-energy-physics funding on one side and nuclear physics funding on the other side.

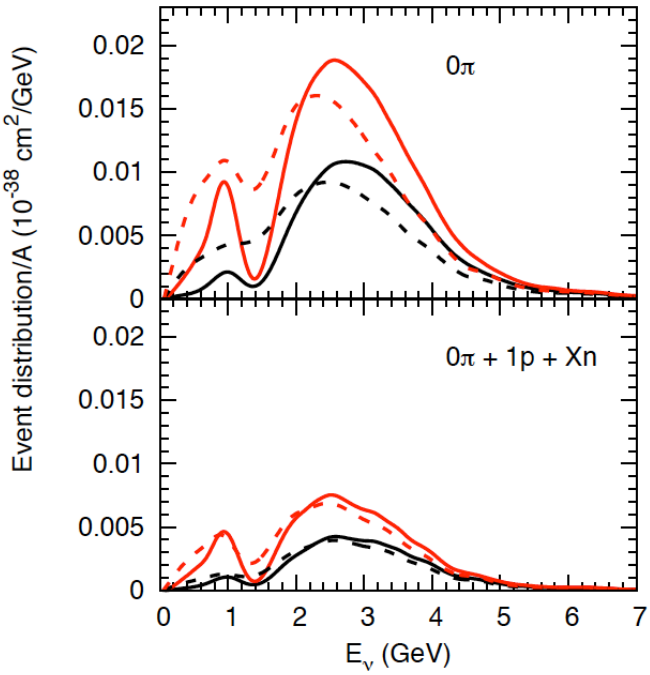

FIG. 8: (Color online) Event distributions per nucleon for electron appearance in the LBNE for $\delta_{CP} = +\pi/2$ and $\delta_{CP} = -\pi/2$ (upper red and lower black curves, resp.), both for true (solid) and reconstructed (dashed) energies. The upper part gives the results for 0 pion events, the lower that for events with 0 pions, 1 proton and X neutrons (from [113].)

D. Neutral Leptons – Very Low-Energy Neutrino Scattering

Understanding of neutrino interactions in the few tens to the ∼100-MeV energy regime is highly relevant to a number of topics at the forefront of nuclear and particle physics such as solar neutrinos, supernovae, dark matter, and nuclear structure.

Supernova neutrino physics: A core-collapse supernova in the Milky Way will create an extremely luminous flash of neutrinos observable in detectors worldwide [116]. To fully interpret the signal, it will be critical to understand the interactions of neutrinos with matter in the tens-of-MeV energy range. Understanding of neutrino-nucleus cross sections is also important for understanding of core-collapse processes and nucleosynthesis in the supernova. Both theoretical work and experimental measurements will be necessary for progress.

Particularly promising for measurements in this regime are stopped-pion neutrino sources, which provide monochromatic 30-MeV ν_μ's from pion decay at rest (DAR), followed on a 2.2-μs timescale by $\bar{\nu}_\mu$ and ν_e with a few tens of MeV from μ decay. The ν spectrum has significant overlap with a typical supernova spectrum (see Fig. 9). High-intensity, sharp-pulse-width, ∼GeV proton beams are desirable for creating such a ν source. Measurements of supernova-neutrino-relevant neutrino-nucleus cross sections in the few tens of MeV range are almost completely unexplored, with only ^{12}C having been measured to the 10% level. Past examples of pion DAR sources are LANSCE and ISIS; a current very-high-quality source is the Spallation Neutron Source at ORNL, which offers a rich neutrino physics program [117]. Another existing source is the Fermilab Booster Neutrino Beam at a far off-axis location [118]. Of particular near-term interest are low-energy neutrino-argon cross sections, required for supernova detection in large LAr detectors, and which can be measured with the small CAPTAIN LAr Time Projection Chamber [119].

Coherent elastic neutrino-nucleus scattering: Coherent elastic neutrino-nucleus scattering is a never-observed process in which the target nucleus recoils coherently via a neutral-current interaction with a neutrino; the process is very cleanly predicted by the standard model. The cross section (10^{-39} cm^2) in the relevant energy region (up to ∼50 MeV) is relatively large, by neutrino-interaction standards. However, due to very small nuclear recoil energies, the process is very difficult to observe experimentally. There are numerous ongoing efforts to detect coherent elastic neutrino-nucleus scattering [120] at reactors and pion decay-at-rest sources [117, 121, 122]. In particular, the CENNS [118] collaboration aims to exploit the FNAL BNB and the COHERENT collaboration [122] aims to use the ∼MW-power SNS. These higher neutrino energy, pion decay-at-rest sources result in relatively larger cross sections and recoil energies and are particularly promising for first measurements using low-energy-nuclear-recoil-sensitive detec-

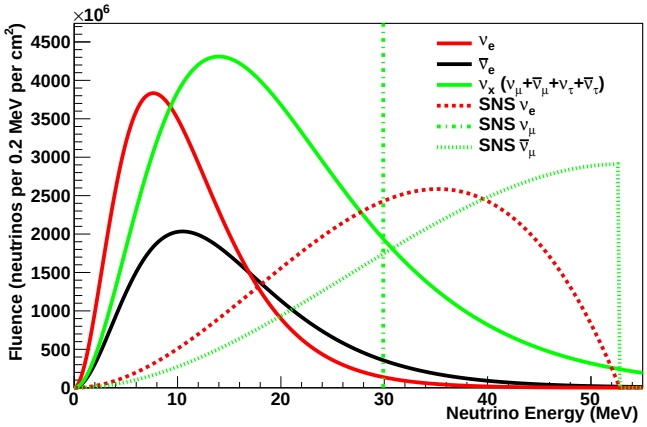

FIG. 9: Solid lines: typical expected supernova spectrum for different flavors; fluence integrated over the ∼15-second burst. Dashed and dotted lines: SNS spectrum; integrated fluence for one day at 30 m from the SNS target.

tors (such as those developed for dark matter detection). A few hundred collected events will be sensitive to currently poorly constrained non-standard neutrino interaction parameters, and could improve limits by an order of magnitude or more. Any deviation from the standard model prediction could be an indication of new physics [123, 124]. The process is also sensitive to non-zero neutrino magnetic moment [125]. The cross section is relevant for the evolution of core-collapse supernovae, and will also be useful for detection of supernova neutrinos [126]. The coherent elastic neutrino-nucleus scattering process also sets the "neutrino floor" background for direct WIMP searches with detectors at approximately the ten-ton scale [127–129] (and could conceivably be used to do astrophysics with very large dark matter detectors [130]). In the longer term, high-precision measurements could probe nuclear structure [131] and could be a new neutral-current tool to search for oscillations of sterile neutrinos [132, 133]. There are also potentially practical applications [134–136].

We conclude the discussion of neutral leptons with Table VII that arranges the experimental neutrino projects according to the principal community that drives the work and provides the capital equipment. Neutrino physics is an area that, perhaps more than any, straddles the line between nuclear physics and high-energy physics. In most cases each of the experiments has participation from both communities.

TABLE VII: Neutrino projects organized by the community that principally is driving them.

Objective	Nuclear	High-Energy
Mass	KATRIN Project 8 NuMECS	
Scattering, Cross-sections		MINERvA CAPTAIN CENNS COHERENT
CP property		LBNE
Solar neutrinos	CLEAN Theia	
Hierarchy		PINGU

E. Charged Leptons – Electron Scattering and New Physics

Precision measurements of the properties of W and Z bosons and their couplings to leptons and quarks have allowed sensitive tests of the electroweak theory. While no significant deviations from Standard Model predictions have been

found, experiments continue to probe for the indirect effects of new physics at a variety of energy scales stretching beyond the reach of high energy colliders, by making more and more precise measurements of electroweak parameters. The most precise measurements of weak neutral current (WNC) couplings have been measured on top of the Z resonance, where the amplitudes are purely imaginary; thus there are no interference terms with real four-fermion amplitudes from new physics effects at higher energy scales. At low Q^2 on the other hand, interference effects might be measurable if sufficient accuracy is achieved [137–140]. WNC interactions at $Q^2 \ll M_Z^2$ are sensitive for example to heavy Z′ bosons or leptoquarks whose effects might be highly suppressed in measurements at colliders [141], and for dark sector mediators that have small admixtures to the Z boson [142].

A powerful low Q^2 technique to access WNC interactions is via parity-violating electron scattering (PVES), which has become a precision tool for novel insights into nuclear and nucleon structure, and searches for physics beyond the Standard Model at $Q^2 \ll M_Z^2$ that are competitive with high energy collider searches. In such experiments, weak-electromagnetic interference leads to a parity-violating asymmetry A_{PV} in the scattering of longitudinally polarized electrons off target particles. For typical fixed target experiments, $A_{PV} \sim 10^{-4} \cdot Q^2$ (GeV)^2 ranges from 10^{-4} to smaller than 10^{-7}. The experimental techniques employed to measure these tiny left-right asymmetries have been steadily refined such that statistical and systematic errors better than 1 part per billion (ppb) are possible [137, 138].

Three published measurements have achieved sufficient sensitive to probe the TeV-scale using very different techniques: ^{133}Cs atomic parity violation (APV) [143], neutrino deep-inelastic scattering measurement (NuTeV) [144] and PVES (SLAC E158) [145]. As we await the restart of the Large Hadron Collider (LHC) at full beam energy and design luminosity, improving these constraints and expanding their reach to include more fermion scattering combinations takes on increased significance, either to help narrow down the physics mechanisms responsible for any observed anomalies or to access discovery space beyond the LHC.

The parity-violating part of the electron-hadron WNC interaction at low Q^2 can be parametrized by four-fermion contact interactions which can then be given in terms of phenomenological couplings C_{ij}, where C_{1j} (C_{2j}) gives the vector (axial-vector) coupling to the jth quark. In the Standard Model, all four couplings are functions of a single parameter: the weak mixing angle $\sin^2\theta_W$. The atomic Cesium weak charge measurement measured one combination of C_{1u} and C_{1d} precisely. At sufficiently forward angles and low Q^2, A_{PV} in elastic electron-proton scattering measures the underlying coherent $2u + d$ e-q amplitude combination to high precision, thus precisely constraining $2C_{1u} + C_{1d}$. This combination is proportional to $1 - 4\sin^2\theta_W$. A 4% measurement of A_{PV} would achieve a precision of $\delta(\sin^2\theta_W) = 0.0007$, the goal of the Qweak experiment [146] in Hall C at Jefferson Lab. The experiment has completed data-taking and published their first result based on commissioning data [15]. A followup experiment called P2 [147], designed as a a flagship measurement of the proposed new MESA facility at Mainz plans a 2% measurement of A_{PV} within the next five years.

The energy upgrade of Jefferson Laboratory will allow precision measurements in parity-violating deep inelastic scattering (PV DIS). One measurement using a 6 GeV beam and the existing high resolution spectrometers in Hall A has recently been published, and helped establish that the axial-quark couplings of light quarks to the Z boson are indeed non-zero [16]. A new dedicated high luminosity apparatus called SoLID, centered around a large superconducting solenoidal magnet [148], would allow $\sim 1\%$ measurements of A_{PV} for the first time over a range of x and Q^2 values. PV DIS allows the isolation of the linear combination $2C_{2u} + C_{2d}$, which is difficult to measure using elastic scattering. Combined with other measurements in elastic electron-proton scattering, precise constraints would be possible on the lesser known axial-vector quark couplings C_{2i}. This would, among other things, provide complementary constraints on various models with new heavy leptophobic Z' bosons [149, 150] and leptoquarks [141].

Figure 10 shows published and planned projections for the extracted uncertainties on $\sin^2\theta_W$, including future collider, PVES and APV weak charge extractions. Perhaps the most sensitive observable is A_{PV} in electron-electron (Møller) scattering to extract the weak charge of the electron, which is also proportional to $1 - 4\sin^2\theta_W$. The SLAC E158 experiment carried out the first measurement of parity violation in Møller scattering [145], setting limits on four-electron contact interactions that are complementary to different chiral combinations accessed at the highest energy electron-positron collider to date, namely LEP-200. There is strong motivation to make further improvements, keeping pace with the improved sensitivity for discovery at the multi-TeV scale by experiments at the Large Hadron Collider. Leveraging the newly available 11 GeV beam at JLab, a new project called MOLLER is being designed to improve on the SLAC E158 measurement by a factor of five [151]. Such a measurement would yield a low energy determination of $\sin^2\theta_W$ at the 0.1% level, comparable the best high energy collider determinations, and the very best in the next decade among potential future measurements at low energy or at colliders. It promises to be the most sensitive probe of a flavor- and CP-conserving amplitude driven by new dynamics in the foreseeable future among planned facilities worldwide.

Another combination of semileptonic WNC couplings (the weak charge of the neutron) may be obtained from PVES on ^{12}C if per-mille level polarimetry becomes feasible [152]. An alternative (and historically crucial) method to constrain this combination is through precision APV measurements. By averaging over the two hyperfine transitions (to separate out the nuclear spin independent effect) the Boulder group [143, 153] obtained an experimental precision

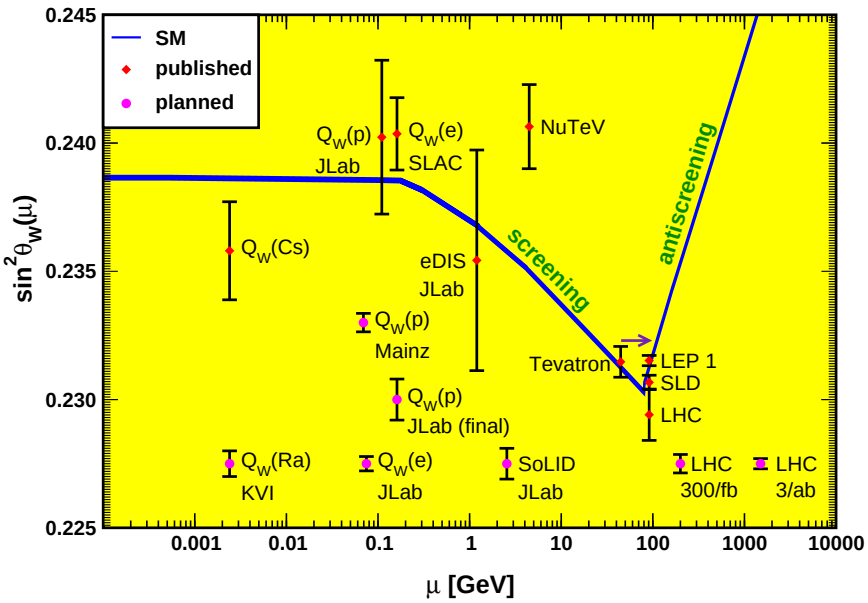

FIG. 10: Published and planned measurements of WNC couplings expressed as the uncertainty in $\sin^2\theta_W$, which runs as a function of the energy scale μ due to higher order electroweak corrections.

of 0.4% in ^{133}Cs mentioned previously. However, there is an uncertainty of similar size from the many-body atomic theory calculations [154, 155] needed to extract the electroweak physics. Several groups have concrete plans to measure parity violating effects in other systems, including at TRIUMF (in Fr) [156], Groningen (in Ra$^+$) [157], and Yale (in molecules) [158]. The atomic theory uncertainties will largely cancel in isotope ratios which will be sensitive to the proton weak charge but at much lower momentum transfer compared to PVES. This may be an effective way to distinguish between new physics involving relatively light degrees of freedom such as a dark Z boson, from new TeV scale physics [159]. The initial efforts will actually target the nuclear spin dependent effects which are sensitive to the remaining operator involving axial quark couplings, but the interpretation in terms of electroweak physics is difficult. One can determine the nuclear anapole moment and study hadronic physics, instead.

F. Charged Leptons – Precision Muon Physics

Fundamental physics investigations using muons span a broad range of motivations and community participation. Figure 11 provides an illustration of Recent, Current, and Future projects, with a further division by the principal community that participates in, or leads, the efforts. As is apparent, nuclear physics overlaps with most projects. Recently completed highlights include the determination of the muon lifetime to 1 ppm precision and the Fermi constant to 0.5 ppm (MuLan), the determination of the weak pseudoscalar coupling, g_P, and a confirmation of a basic low-energy effective field theory prediction (MuCap), an order-of magnitude improvement of the Michel parameters (TWIST), new stringent limits on the CLFV decay $\mu \to e\gamma$ (MEG), and a precise determination of the proton charge radius from the muonic Lamb shift measurement (PSI). Current and future projects include followups to the μp studies using light nuclei (CREMA), muon capture on the deuteron to establish a fundamental low-energy constant related to pp fusion (MuSun), upgrades to MEG for another order of magnitude sensitivity, additional CLFV tests using coherent $\mu \to e$ conversion and $\mu \to eee$, muonium hyperfine splitting, and two new muon $g-2$ experiments. In this short space, we cannot describe these efforts in any detail, but we will mention the U.S. led $g-2$ experiment. Strongly endorsed during the previous long range plan exercise by the nuclear physics community, and also in the recent P5 prioritization by the high-energy community, this large-scale international effort will provide an important result in the current LRP cycle. We will discuss CLFV in a little more detail in the next section.

Arguably the strongest hint of new physics now existing, is the $> 3\,\sigma$ deviation between the experimental measure-

ATOMIC	NUCLEAR	HIGH ENERGY
Muonium **Mu HFS**		
Lamb Shift **CREMA** (r_p)	μp scattering **MUSE** (r_p)	
	μp capture **MuCap** (g_P)	
	μd capture **MuSun** (L_{1A})	
	μ^+ lifetime **MuLan** (G_F)	
	Michel Parameters **TWIST**	
	Anomalous moment **g-2 Expts**	
	μEDM **g-2 Expts**	
		cLFV **MEG**
		cLFV **Mu2e & COMET**
		cLFV **Mu3e**

FIG. 11: Table indicating recent (red), current (blue) and future (green) muon experiments, organized by principal community that drives the work.

ment [160] and the theoretical prediction (see Ref. [161]) for the muon anomalous magnetic moment, $a_\mu \equiv (g-2)/2$. The anomalous contributions arise from quantum fluctuations—loop effects—which is where new physics can also hide. QED and Weak contributions are known to very high precision, but leading-order hadronic vacuum polarization (HVP) and higher-order hadronic light-by-light (HLbL) scattering are more challenging, having a combined uncertainty of ~ 0.42 depending on the actual evaluation technique. A vigorous effort is ongoing world-wide to improve the SM hadronic terms. Promising tools include lattice efforts, additional measurements of data entering the HVP evaluation, and new discussion of data-driven efforts related to pinning down HLbL terms [162–164] (see also [165]). This is motivated by the new U.S. led Fermilab E989 experiment, which aims for a final precision of 0.14 ppm. The experiment is under construction with expected data taking to begin in early 2017. It will reuse the now relocated BNL storage ring in combination with a modern update of all components and a custom high-purity muon beamline. Order-of-magnitude improvements in the muon EDM limits are determined parasitically with normal data taking.

The magnetic moment is a flavor- and CP-conserving, chirality-flipping, and loop-induced quantity, which is in contrast to many high-energy collider observables at the LHC and other precision experiments that might test CP- or flavor-violation. What kind of physics might a non-SM compliant a_μ imply? For many models, this can be illustrated in a general way following a relation discussed in [166] in which new physics (N.P.) contributions will scale as $\delta a_\mu(N.P.) = \mathcal{O}[C(N.P.)] \times (m_\mu/M)^2$ where M is a new physics (N.P.) mass scale and C is a coupling strength, related to any new physics contributions to the muon mass; that is, $C(N.P.) \equiv (\delta m_\mu(N.P.)/m_\mu)$. Stockinger demonstrates how this relation can show that typical new physics models will give very different predictions for a_μ. Figure 12 gives ranges for non-SM contributions for various coupling strengths, C. For muon mass generated by radiative effects, $C(N.P.) = \mathcal{O}(1)$, which indicates that the current a_μ is probing the multi-TeV scale. For $\mathcal{O}(\alpha/4\pi)$ models, one could argue that a_μ is largely incompatible owing to the light implied masses. But for models with enhanced coupling—including SUSY, unparticles and various extra dimensions—the expected mass range corresponds to what can be measured at the LHC, owing to the enhanced coupling, for example from a $\tan\beta$ range of $5-50$ in this plot for SUSY models. The horizontal bands show the current δa_μ limits and an expected combined theory and experimental future sensitivity. What is missing here is the possibility to obtain a large δa_μ from very weakly interacting and very light particles, such as dark photons. This would correspond to another narrow band hugging the vertical axis, crossing the Δa_μ region in the 10 - 100 MeV mass range and having a very small coupling.

G. Charged Leptons – Flavor Violation with Muons

Electron number, muon number, and tau number are known to be violated in nature – neutrinos oscillate – and hence all so-called charged-lepton flavor violating processes (CLFV) will occur at some order in perturbation theory. The rates for such processes, however, cannot be estimated model-independently. Many experimental searches for CLFV are carried out at B factories. Examples include: $\tau \to eee$, $\tau \to \mu\mu\mu$, $\tau \to e\gamma$, and $\tau \to \mu\gamma$ but many others exist. Impressive sensitivity has been achieved with branching ratios typically at the 10^{-8} level and the future promises order-of-magnitude improvements once Belle-II is operational.

It is, however, the low-energy muon reactions (1) $\mu^+ \to e^+\gamma$, (2) $\mu^+ \to e^+e^-e^+$, and (3) the coherent conversion of a muon to an electron in a muonic atom, $\mu^- N \to e^- N$, that are by far the most sensitive to new physics. The

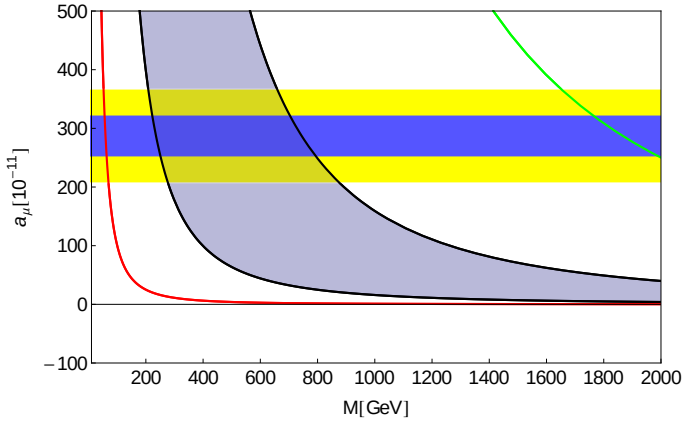

FIG. 12: Generic classification of mass scales vs. a_μ contributions from new physics sources such as radiative muon mass generation (red), Z', W', UED, or Littlest Higgs models with weak coupling (green), or typical unparticle, or various extra dimension models, or SUSY having enhanced coupling; here a $\tan\beta$ range of $5-50$ is used (grey). The yellow horizontal band corresponds to the current difference between experiment and theory and the blue band is an improvement with a combined theory and experimental error of 34×10^{-11}. Courtesy D. Stockinger [167].

MEG Collaboration at PSI has studied $\mu^+\to e^+\gamma$ and established limits on the branching ratio of $< 5.7\times10^{-13}$ (90% C.L.) [168]. They have upgrade plans in place to improve by an order of magnitude. In the planning stage are two experiments to search for $\mu^- N\to e^- N$ conversion at single event sensitivities approaching 10^{-17}, Mu2e [169] at Fermilab and COMET [170] at J-PARC More recently, a proposal was put forward at PSI to explore $\mu^+\to e^+e^-e^+$ decays assuming the branching ratio is above 10^{-15} [171]. All of these experiments are indeed quite ambitious as the BR's of interest are extraordinary tiny.

To gauge the sensitivity and complementarity of the different muon CLFV processes, it has become customary to compare, for example the sensitivity of reactions (1) and (3) using an effective Lagrangian of the form [172]

$$\begin{aligned}\mathcal{L}_{\rm CLFV} &= \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar\mu_R\sigma_{\mu\nu}e_L F^{\mu\nu}+h.c.\\ &+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar\mu_L\gamma_\mu e_L\left(\bar u_L\gamma^\mu u_L+\bar d_L\gamma^\mu d_L\right)+h.c.\,.\end{aligned}\tag{6}$$

The subscripts L, R indicate the chirality of the different Standard Model fermion fields, $F^{\mu\nu}$ is the photon field strength and m_μ is the muon mass. The dimensionful parameter Λ is the effective new-physics mass scale, while the dimensionless parameter κ governs the relative size of the two different types of operators. The magnetic-moment type operator in the first line of Eq. (6), dominant for $\kappa\ll1$, directly mediates $\mu\to e\gamma$ and mediates $\mu\to eee$ and $\mu\to e$ conversion in nuclei at order α. The four-fermion operators in the second line of Eq. (6), dominant for $\kappa\gg1$, mediate $\mu\to e$ conversion at the leading order and $\mu\to e\gamma$, $\mu\to eee$ at the one-loop level.

The sensitivity to Λ as a function of κ for $\mu\to e\gamma$ and $\mu\to e$ conversion efforts is depicted in Fig. 13(Left). CLFV already probes Λ values close to 1000 TeV and next-generation experiments will start to probe $\Lambda\sim10^4$ TeV. A $\mu\to e$ conversion experiment is "guaranteed" to outperform a $\mu\to e\gamma$ experiment for any value of κ as long as it is a couple of orders of magnitude more sensitive. A similar analysis can be performed to compared the reach of $\mu\to e\gamma$ with that of $\mu\to eee$ [172]. Comparing, in such a model independent way, $\mu\to e$-conversion and $\mu\to eee$ is not possible. Concrete models are discussed, for example, in [172, 173].

It is illustrative to compare, as model-independently as possible, new physics that mediates CLFV and the new physics that may have manifested itself in precision measurements of the muon anomalous magnetic moment. New, heavy physics contributions to the muon $g-2$ are captured by the following effective Lagrangian:

$$\mathcal{L}_{g-2}\supset\frac{m_\mu}{\Lambda^2}\bar\mu_R\sigma_{\mu\nu}\mu_L F^{\mu\nu}+h.c.\,.\tag{7}$$

Current $g-2$ data point to $\Lambda\sim8$ TeV. Eq. (7), however, is very similar to Eq. (6) in the limit $\kappa\ll1$, keeping in mind that Λ in Eq. (7) need not represent the same quantity as Λ in Eq. (6) in the limit $\kappa\ll1$. We can relate Λ in Eq. (7) to that in Eq. (6) in the following suggestive way: $(\Lambda_{\rm CLFV})^{-2}=\theta_{e\mu}(\Lambda_{g-2})^{-2}$, where the parameter $\theta_{e\mu}$ measures how flavor-conserving is the new physics. If the new physics is flavor-indiferent, $\theta_{e\mu}\sim1$, negative searches for $\mu\to e\gamma$ already preclude a new physics interpretation to the muon $g-2$ results as these constrain $\Lambda\gtrsim1000$ TeV. On the other hand, if the muon $g-2$ discrepancy is really evidence for new physics, searches for $\mu\to e\gamma$ reveal that the "amount" of flavor violation in the new physics sector is very small: $\theta_{e\mu}<10^{-4}$.

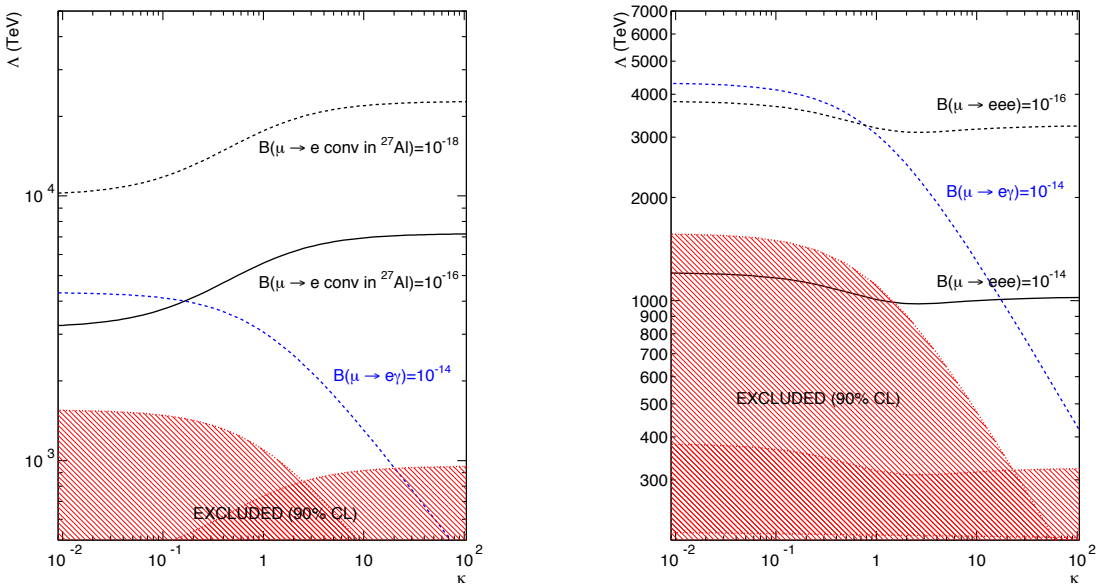

FIG. 13: [Update of [172]]. Left: Sensitivity of a $\mu \to e$ conversion in ^{27}Al experiment that can probe a normalized capture rate of 10^{-16} and 10^{-18}, and of a $\mu \to e\gamma$ search that is sensitive to a branching ratio of 10^{-14}, to the new physics scale Λ as a function of κ, as defined in Eq. (6). Also depicted is the currently excluded region of this parameter space. Right: Similar analysis, comparing $\mu \to e\gamma$ and $\mu \to eee$ (see [172]).

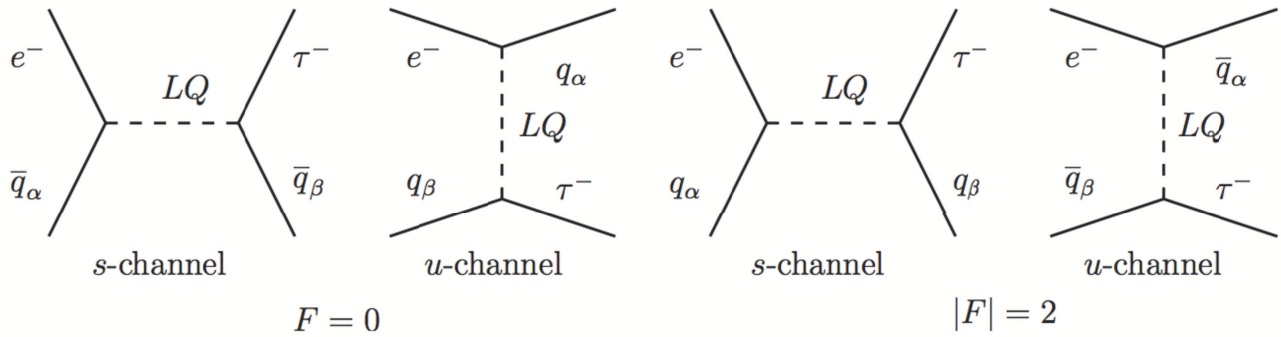

FIG. 14: Feynman diagrams for $e \to \tau$ scattering processes via leptoquarks, which carry fermion number $F = 3B + L$ equal to 0 or ± 2 [179]

H. Charged Leptons – Flavor Violation at an Electron Ion Collider

While the most sensitive experimental reach is for the $e \leftrightarrow \mu$ transition, the $\tau \to e$ process is being probed in B-factories, as discussed earlier. Recently, there have been studies carried out to investigate the sensitivity of a high luminosity polarized lepton-light ion collider (EIC) [174] to $e \to \tau$. The EIC is currently under consideration as a high priority new construction project in the nuclear physics community. In a lepton-hadron collision, one would have the kinematic sensitivity in a collider environment to search for the extremely rare toplogy where an electron converts to a tau lepton. Such sensitivity would be impossible in a fixed target experiment due to the large and irreducible QCD background. Indeed, the only existing searches for this topology was carried out at the HERA electron-proton collider [175–177].

One possible mechanism for this specific CLFV process is mediation by new heavy boson known as a leptoquark, which carries both lepton and baryon quantum numbers and appears naturally in many SM extensions such as Grand Unified Theories, supersymmetry, and compositeness and technicolor models. Figure 14 shows the Feynman diagrams that could be responsible for the CLFV transition that might be observed at an EIC, extending the reach beyond the most sensitive published search limit [178].

A recent study has shown that an EIC, with 90 GeV center-of-mass energy, could surpass the current limits with an integrated luminosity of 10fb^{-1} [179]. The study also showed that the EIC could compete or surpass the updated leptoquark limits from rare CLFV tau decays for a subset of quark flavor-diagonal couplings. A follow-up study beyond this, including knowledge of inefficiencies from the H1 and ZEUS collaborations for τ reconstruction, indicates that $100 - 200$fb^{-1} luminosity integrated over the EIC lifetime [180] will be required. Over the lifetime of the EIC, the $e \to \tau$ reach would thus be comparable to the reach of rare τ decays at future high-luminosity super-B factories.

IX. LOW ENERGY WEAK INTERACTIONS

A. Precision semi-leptonic decays as probes of new physics

1. *Overview and Recent Accomplishments*

Measurements of the decay of mesons, neutrons and nuclei provide the most precise and sensitive characterization of the weak charged current interactions of quarks. Measurements of neutron decay also provide critical input to our understanding of Big Bang Nucleosynthesis predictions for the primordial ^{4}He abundance. The last planning period has seen real progress in this subfield, with new theoretical tools providing a sharper focus for planned measurements and significant investment in facilities and experimental techniques resulting in exciting opportunities emerging for the next five years.

Because high precision tests of nuclear decay rates require a very precise characterization of the states involved in the decay, measurements in this field rely heavily on decays between isobaric analog states, including the superallowed $0^+ \to 0^+$ decays, mirror decays and neutron decay. The superallowed decays, in particular, through decades of refinement, have become the basis for our most precise determination of the vector coupling strength of the quarks. As we detail in the subsection "Beta-decay in phenomenology in the LHC Era", these measurements provide the basis for constraints for BSM physics at the expected sensitivity level of the LHC and beyond. Measurements the neutron also play an important role in this subfield, already providing the definitive value for the axial coupling constant and providing a path to nuclear structure-independent measurements of vector coupling strength and improved limits on BSM couplings.

Progress in this field is driven in large part by the development of intense beams or sources which can be dedicated to long runs and refined to optimize signal to background issues. In the last planning period, the U.S. low energy nuclear physics program supported the commissioning of the world's strongest pulsed cold neutron beamline for fundamental neutron physics at the Spallation Neutron Source (SNS), and one of the world's strongest ultracold neutron sources at a pulsed spallation target at the Los Alamos Neutron Science Center (LANSCE). These sources have already provided important progress, with improved measurements of the beta-asymmetry with ultracold neutrons (UCNA) and the neutron lifetime with cold neutrons (the BL-1 experiment at NIST). Moving forward, these new sources and the upgraded cold neutron beamlines at the National Institute for Standards and Technology (NIST) provide a firm basis for an experimental program which includes several high profile neutron decay measurements both of angular correlations and the neutron lifetime. As we detail in the section "Opportunites for the Next Planning Period," the envisioned program to perform world-leading measurements of the neutron lifetime both with cold neutron beams and ultracold neutrons clearly puts U.S. fundamental neutron research in a very strong position, with roughly 0.1% precision measurements planned in the next five years.

Major research and development efforts have also produced significant new resources and opportunites for measurements in nuclear systems. Here the US continues to maintain a world-leading program in the characterization of superallowed decays (primarily based at Texas A & M University). The last planning period also saw the establishment of a unique and competitive fundamental symmetries program at Argonne which utilizes the ion-cooling and trapping infrastructure developed for the Facility for Rare Isotope Beams (FRIB) and the development of the world's strongest source of ^{6}He for measurements of angular correlations and beta spectra at the University of Washington. The decay of ^{6}He involves a low Z system with a very simple, pure Gamow-Teller decay scheme and a moderately low beta-decay endpoint, ideal for high sensitivity probes for BSM tensor couplings. Given the interest in ^{6}He decay (with 5 different experiments planned for this nucleus at various national and international laboratories), we see the potential for constraints well beyond LHC sensitivity for BSM tensor couplings emerging from the US experimental program.

Finally, the $\pi \to l\nu$ (π_{l2}) decays, where $l = e, \mu$, are sensitive to small deviations from the $(V-A)$ form of the weak interaction: the low branching ratio $R^{\pi}_{e/\mu} = B(\pi \to e\nu)/B(\pi \to \mu\nu) \simeq 1.2 \times 10^{-4}$ is a consequence of the weak $(V-A)$ helicity suppression. While the theoretical uncertainty of the π_{l2} process is extraordinarily low, $dR^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 10^{-4}$, the experimental world average uncertainty is $\sim 40\times$ larger. At the 10^{-3} level and below, $R^{\pi}_{e/\mu}$ sets a competitive

direct limit on the pseudoscalar weak coupling, and at loop level on other non-SM admixtures, e.g., axial, vector and scalar. It also sets limits on masses of additional charged Higgs bosons, as well as on certain parameters in supersymmetric extensions of the SM. Alternatively, $R^{\pi}_{e/\mu}$ provides the most sensitive probe of lepton universality, affecting, among others, the neutrino sector. Currently two projects, PEN at PSI and PIENU at TRIUMF, are each aiming to improve the experimental precision of $R^{\pi}_{e/\mu}$ to about 5 parts in 10^4. Both have finished taking data and are in the analysis phase, with results expected in the near term.

One area in which theoretical guidance has been crucial has been in pointing out the potential impact of new constraints on scalar and tensor couplings. A major step forward for the field has been the development of a model independent analysis using Effective Field Theory (EFT), permitting a direct comparison between constraints from low energy beta decay and those from the accelerator based experiments such as the LHC. Experimental limits for these coupling constants in low energy decays can be extracted from "integral" measurements of the angular correlation parameters and the decay rate, but they also produce characteristic signatures in the beta energy dependence of angular correlations and decay rates. Several opportunities have emerged to explore possible "post-LHC" limits, including neutron decay measurements with state-of-the-art Si detectors for high precision spectroscopy, and also possibly utilizing the emerging technology of single electron spectroscopy through measurements of relativistic synchrotron emission. Although these measurements require typically $\simeq 0.1\%$ to directly competitive with model independent limits from the LHC, our section on "Beta-decay phenomenology in the LHC era," also details strong motivation to push for another order of magnitude greater sensitivity, to provide constraints on explicit models, such as the Minimal SuperSymmetric Model (MSSM).

Section III highlights the experimental accomplishments of the field over the last planning period. We review the current status of the theoretical analysis of low energy decays, which has recently taken some remarkable steps forward. We then conclude with a brief prospectus for the major opportunities in the timeframe of the next long-range plan.

2. *Beta-decay phenomenology in the LHC era*

While historically beta decays have played a central role in shaping the Standard Model (SM) [181–183], they have evolved to provide deep probes of new physics. In this section we summarize recent developments in the theoretical framework needed to assess the impact of beta-decay observables in light of other low- and high-energy searches for BSM physics.

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 decay measurements in nuclei, neutrons and mesons probe the existence of non-SM interactions, which effectively induce violations of the universality relations and/or novel non-$(V-A)$ structures. The low-energy CC Hamiltonian receives contributions by many classes of SM extensions, so that beta decay measurements are a "broad band" probe of physics beyond the Standard Model (BSM): 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 in *any* model are encoded in ten non-standard couplings $\epsilon_i, \tilde{\epsilon}_j$:

$$\mathcal{L}^{BSM}_{CC} = -\sqrt{2}\, G_F\, V_{ud} \sum_{i=L,R,S,P,T} \left\{ \epsilon_i\ \bar{e}\, \Gamma^e_i\, \nu_{eL} \cdot \bar{u}\, \Gamma^q_i\, d \ +\ \tilde{\epsilon}_i\ \bar{e}\, \tilde{\Gamma}^e_i\, \nu_{eR} \cdot \bar{u}\, \Gamma^q_i\, d \right\}\,, \tag{8}$$

where $\nu_{L,R} = 1/2(1 \mp \gamma_5)\nu$ and $\Gamma^{q,e}_L = \Gamma^e_R = \gamma^\mu(1-\gamma_5)$, $\Gamma^q_R = \tilde{\Gamma}^e_{L,R} = \gamma^\mu(1+\gamma_5)$, $\Gamma^{q,e}_S = 1$, $\Gamma^{q,e}_P = \gamma_5$ $\Gamma^{q,e}_T = \sqrt{2}\sigma_{\mu\nu}$, $\tilde{\Gamma}^e_{S,P,T} = \Gamma^e_{S,P,T}$. The non-standard couplings $\epsilon_\alpha, \tilde{\epsilon}_\beta$ are dimensionless: 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. Table VIII contains a summary of low-energy probes of non-standard CC couplings, including the most constraining observable and the current sensitivity. This table summarizes a broad array of experimental and theoretical input, and for more details we refer to Refs. [184, 185]. It is worth emphasizing that all bounds rely on calculations of appropriate hadronic matrix elements and radiative corrections.

In any concrete model, the new physics that generates the ϵ_α's affects other observables as well, such as precision electroweak tests and collider processes. In the "heavy BSM benchmark" in which new physics exists at the few TeV mass range, collider data can be analyzed in terms of the very same ϵ_α couplings. In particular, the non-standard couplings affect the $pp \to e + \nu + X$ at the LHC: from the agreement of the SM distributions with data one can extract bounds on the ϵ_α's ranging from 0.3% to 1.0% [52, 53]. In this heavy BSM benchmark, current data imply that beta decays are generally more competitive than LHC in constraining the ϵ_α's, while they are less competitive in constraining the $\tilde{\epsilon}_\beta$'s (quadratic sensitivity). While for $\epsilon_{L,R,P}$ beta decays are by far more constraining than LHC, an interesting competition is expected in the next few years for the scalar and tensor couplings $\epsilon_{S,T}$, as illustrated in Fig. 15 (left panel).

If the new physics scale is below the TeV, a model-independent analysis of LHC constraints is not possible, and one has to study explicit models. Beta decay observables, including $\Delta_{\rm CKM} = 1 - V_{ud}^2 - V_{us}^2 - V_{ub}^2$ and decay correlations, have been analyzed in great detail within supersymmetric scenarios [47–49, 186]. Recent studies within models with compressed mass spectrum suggest that super-partner loops could still affect beta decays at the level of $\Delta_{\rm CKM} \sim 10^{-4}$ while remaining essentially invisible at the LHC [49, 50]. An example of an interesting correlation between low-energy semi-leptonic processes is displayed in Fig. 15 (right panel).

In summary, beta decays with a precision in the range $0.1\% \to 0.01\%$ remain a unique probe of new physics at the TeV scale. A discovery window exists well into the LHC era, both in the "heavy BSM benchmark" [53] and in explicit lower-scale models, such as Supersymmetry with a compressed spectrum [50].

Non-standard coupling	Observable	Current sensitivity	Prospective sensitivity
$\mathrm{Re}(\epsilon_L + \epsilon_R)$	$\Delta_{\rm CKM} = \lvert V_{us}\rvert^2 + \lvert V_{us}\rvert^2 + \lvert V_{ub}\rvert^2 - 1$	$\sim 0.05\%$	$< 0.05\%$ *
$\mathrm{Im}(\epsilon_R)$	D_n	$\sim 0.05\%$	
$\epsilon_P,\ \tilde{\epsilon}_P$	$R_\pi = \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)}$	$\sim 0.05\%$	
$\mathrm{Re}(\epsilon_S)$	$b,\ B,\ [\tilde{a},\ \tilde{A},\ \tilde{G}]$	$\sim 0.5\%$	$< 0.3\%$
$\mathrm{Im}(\epsilon_S)$	R_n	$\sim 10\%$	
$\mathrm{Re}(\epsilon_T)$	$b,\ B,\ [\tilde{a},\ \tilde{A},\ \tilde{G}],\ \ \pi \to e\nu\gamma$	$\sim 0.1\%$	$< 0.03\%$
$\mathrm{Im}(\epsilon_T)$	Rs_{Li}	$\sim 0.2\%$	$\sim 0.05\%$
$\tilde{\epsilon}_{\alpha\neq P}$	a, b, B, A	$\sim 5 - 10\%$	

TABLE VIII: Summary of current and prospective sensitivities to non-standard CC couplings defined in Eq. (8). First column: combination of couplings. Second column: observable. Third and fourth columns: current and prospective sensitivity. Decay correlations a, A, B, D, R and Fierz interference term are defined in Refs. [184, 185].

3. *Opportunities for the Next Planning Period*

Much of the explicit guidance for the next planning period comes from the recent theoretical developments presented in the previous section. This work has permitted the field to put effort into measurements with clear impact in the broader context of ongoing and planned measurements at the LHC and other high energy probes of this physics. As a part of our planning for this field, we see an urgent need to support continued investigation into the theoretical issues of precision measurements, including (i) particle phenomenology, essential to connect low-energy measurements to the changing high-energy landscape; (ii) lattice QCD calculations of nucleon and meson matrix elements, and (iii) nuclear structure calculations. In particular, in order to pursue the CKM unitarity tests at unprecedented levels ($\delta(\Delta_{\rm CKM}) : 0.06\% \to 0.02\%$), additional scrutiny is needed in the extraction of both V_{us} from K decays (meson form factors from lattice QCD), and V_{ud} from nuclear $0^+ \to 0^+$ decays (with emphasis on radiative and isospin-breaking corrections). Moreover, for high precision probes of scalar and tensor couplings, involving beta spectra and decay correlations, improved calculations of recoil-order terms will be needed. For light nuclei, this is an area in which Quantum Monte Carlo calculations [188] could have a very high impact.

From the updated theoretical perspective we presented in the previous section, it is clear that the ongoing program of beta decay measurements in the U.S. is well motivated. In particular, the CKM unitarity test provides significantly more stringent constraints on charged current interactions with (V,A) structure than the current or planned limits from the LHC. Hence, the current experimental program to refine our understanding of the nuclear structure-dependent corrections for the superallowed Fermi decay data set is important, as well as developing an independent extraction of the CKM matrix element V_{ud} from the neutron and mirror nuclei. For neutron and mirror nuclear decays, this requires measurement of both angular correlations and lifetimes. Concrete steps are planned to accomplish these goals in the next LRP period, including: (1) for superallowed decays, detailed analysis of mirror decays to the decays

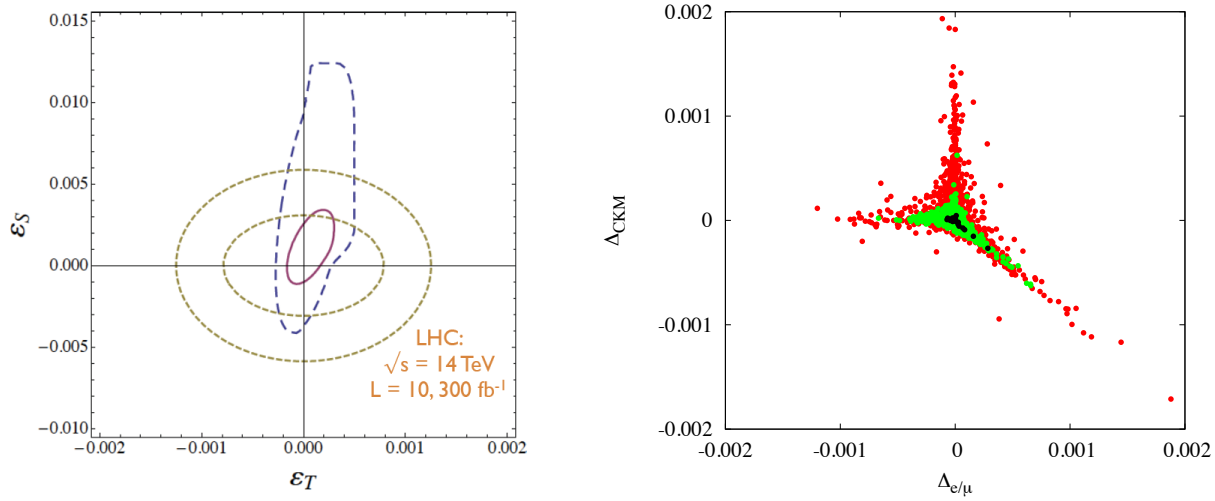

FIG. 15: LEFT PANEL: Projected joint 90% CL constraints on (ϵ_S) and (ϵ_T) from future beta decay measurements and the LHC at $\sqrt{s} = 14$ TeV. The low-energy constraints correspond to 0.1% measurements of B, b in neutron decay and b in ^{6}He decay, under two different scenarios for the QCD uncertainties in the scalar and tensor nucleon-level matrix elements, namely $g_{S,T}$: quark model [187] (large dashed contour) and lattice QCD [52, 55] (smaller solid contour). RIGHT PANEL: Correlation between $\Delta_{\rm CKM}$ and $\Delta_{e/\mu} \equiv R_\pi/R_\pi^{SM} - 1$ in the MSSM [49]. The red points (dark grey) arise from a generic parameter space scan. The green points (light grey) arise after applying the constraints from precision electroweak tests. The black points arise after applying the constraints from direct searches at the LHC. The three branches correspond to the following scenarios for the sfermion spectra: the vertical branch corresponds to light squarks, which have been largely ruled out by the LHC, and heavy sleptons; the right branch corresponds to light smuons and heavy selectrons and squarks; the left branch corresponds to light selectrons and heavy smuons and squarks.

in the current high precision dataset, to permit very high precision tests of the structure dependent corrections; (2) measurements of the neutron lifetime (BL-3 and UCNτ) and angular correlations (UCNA and Nab) near or at the precision level required for competitive extraction of V_{ud} through $V_{ud} = [4908.7(1.9)s/(\tau_n(1+3g_A^2)]^{1/2}$ [189], namely $\delta\tau_n < 0.3$ s, and $\delta a/a, \delta A/A < 0.1$ %; (3) continued refinement of angular correlation and lifetime measurements in select mirror decays, including ^{37}K and ^{19}Ne.

The motivation and opportunity for improved measurements of the neutron lifetime during the next planning period is particularly noteworthy. In addition to playing an important role in BSM constraints, the uncertainty in the lifetime also defines the limiting uncertainty in BBN predictions of the primordial ^{4}He abundance [190], a parameter also closely tied to the number of light, relativisitic degrees of freedom in the early universe, N_ν [191]. At present, the precision with which BBN predictions can be tested is limited by the observations, but steady progress is being made on this front, with precision of the observations (roughly a percent) already at a level to suggest interesting contraints on N_ν. On the experimental side, the development of a new approach to the measurement of the absolute flux for cold neutron beams experiments by the BL-1 collaboration has lead to a sharpening (now at the 4σ level) of the disagreement between the lifetimes extracted from UCN storage and beam experiments. In order to resolve this issue and eliminate the neutron uncertainty from BBN predictions, improved measurements near the 0.1% level of the neutron lifetime in both beam *and* UCN storage experiments are required. The US is in a position to lead this effort, with improvements to the cold and ultracold neutron source intensities, and very competitive experimental approaches for both beam (BL-3) and UCN storage (UCNτ) experiments.

A major effort has also been launched at the Fundamental Physics Beamline at the SNS to measure the electron-neutrino correlation at the 0.1% level in the Nab experiment. This experiment should determine the axial coupling constant at the precision level required to determine V_{ud} from neturon decay at the same level as the superallowed decays, as well as making a contribution to constraints on BSM (S,T) couplings. The sources of systematic error for this approach are significantly different from the experiments which measure the correlation between the emission direction of the decay beta particle and the neutron spin (the beta-asymmetry) which provide the most precise values at present for the axial coupling constant. The distinct nature of the approach of Nab will contribute to a more robust world average for the axial coupling constant. The UCNA experiment (which determines the beta-asymmetry, using ultracold neutrons for the first time) also has a run planned to improve their precision to the 0.35% level or below (with 0.2% being the nominal ultimate sensitivity goal for this experiment).

A unique opportunity exists to utilize beta decay to place improved constraints on BSM interactions with (S,T)

structure. The suggested methodology here involves primarily measurements of the beta spectrum and the beta energy dependence of angular correlations, to determine the possible contributions of Fierz terms in beta decay. In this context, ^{6}He decay has become a focus of efforts of four or more collaborations worldwide, with both angular correlation and spectrum measurements envisioned. In the U.S., major efforts by a UW-ANL collaboration and at NSCL are in the planning phases or underway. The recent success of Project 8 in demonstrating high precision, single electron spectroscopy could provide a large impact to envisioned spectroscopy efforts in the next planning period. The neutron decay program also has spectroscopy measurements planned, with highly segmented, thick Si detectors being implemented in the Nab experiment and the UCNB R&D project for this purpose.

For higher precision probes (in particular utilizing beta spectroscopy) in nuclei to push to post-LHC sensitivity, our characterization of the recoil-order terms and nuclear structure effects will require refinement. Hence, precision measurements programs such as the ^{8}Li, ^{8}B will be important benchmarks of our ability to probe the physics of charged current at the recoil order.

B. Hadronic Parity Violation

While the weak interaction is well understood at the quark level, our knowledge and understanding of the hadronic weak interaction is still limited. The only tool available for studying neutral-current effects is hadronic parity violation, as these effects are suppressed in flavor-changing hadronic decays. Hadronic weak interaction has, for 30 years, been described by a meson exchange model (DDH) [192], where observables are expressed as linear combinations of meson couplings. Modern theoretical frameworks include Effective Field Theory [193] as well as Lattice QCD [194]. EFTs are model independent and provide systematic theoretical error estimates, as well as a connection to QCD via symmetry principles. EFTs are an excellent tool for interpreting experimental data and calculations of parity-violating observables in systems of up to five nucleons are currently possible. Lattice QCD has also become a reliable tool for HPV calculations, and future experiments present exciting opportunities to test precise predictions.

The existence of high-intensity sources of both neutrons and photons allows for a series of measurements that will greatly elucidate the nature of hadronic parity violation. The forthcoming experimental result from the NPDGamma experiment [195, 196] will yield a measurement of the ΔI=1 part of the interaction, corresponding to weak pion exchange, unencumbered by nuclear effects. Further measurements are necessary to determine more hadronic parity-odd amplitudes. Unlike NPDGamma, other measurements are sensitive to combinations of different amplitudes, and multiple experiments are needed to extract them.

The $n+^3$He experiment to search for a parity-odd asymmetry in the $\vec{n}+^3\mathrm{He} \rightarrow p+T+765$ keV reaction is preparing to run at the Spallation Neutron Source. This is a natural follow-on to NPDGamma and is sensitive to $\Delta I = 0, 1,$ and 2 parts of the hadronic weak interaction. The projected error on the asymmetry is 1.6×10^{-8} and the experiment will be commissioned in early 2015. The Neutron Spin Rotation (NSR) collaboration, which proposes to measure polarized slow neutron spin rotation in ^{4}He, is gearing up for data taking on the new NG-C beamline at NCNR at NIST [197]. This measurement will also help constrain linear combinations of parity-odd transition amplitudes. Both $n+^3$ He and NSR experiments are well-developed, mature efforts which will yield results in the next few years.

The next experimental opportunity that can greatly advance our understanding of the hadronic weak interaction is the measurement of the parity-odd helicity dependence of the photodisintegration of the deuteron near threshold, $\vec{\gamma} + D \rightarrow n + p$. This observable is sensitive to the elusive $\Delta I = 2$ weak amplitude and is especially compelling for theory, as it arises due to one $\Delta I = 2$ effective 4-quark operator above Λ_{QCD} and is also the most accessible channel for a calculation from the Standard Model using lattice gauge theory. This experiment could be performed at the HIγS facility at the Triangle Universities Nuclear Laboratory (TUNL), with an upgrade to increase the beam intensity by two orders of magnitude as well as provide the capability of rapid photon helicity reversal. This two-stage upgrade process would allow for a measurement of the parity-violating asymmetry of the photodisintegration of the deuteron to an accuracy of 10^{-8}. An upgraded facility would also be useful for future parity-violation experiments in other few body systems.

A discovery of time reversal violation in any hadronic system is clearly of fundamental importance. It has been known for decades that, in certain heavy nuclei, neutron p-wave resonances enhance parity-odd amplitudes by several orders of magnitude. The same amplification mechanism works also for a P-odd T-odd neutron-nucleus forward-scattering amplitude. A transmission experiment to search for a P-odd and T-odd term in the forward neutron-nucleus scattering amplitude using polarized neutrons and polarized nuclear targets shares with electric dipole moment the property of being a null test for time reversal invariance. Advances in the ability to produce eV neutron beams of high polarization and in the ability to polarize macroscopic amounts of the relevant nuclei coupled with the appearance of bright pulsed spallation neutron sources (SNS and JSNS) make it timely to reconsider the scientific reach and potential of this approach in light of the progress since the last Long-Range Plan.

$\nu_\mu \to \nu_\mu$	atmospheric, SBL	$\nu_\mu \to \nu_e$	SBL
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	atmospheric, SBL	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL, OscSNS
$\nu_e \to \nu_e$	SOX	$\nu_e \to \nu_\mu$	?
$\bar{\nu}_e \to \bar{\nu}_e$	PROSPECT, IsoDAR, SOX	$\bar{\nu}_e \to \bar{\nu}_\mu$	?

TABLE IX: List of possible oscillation channels and experiments which can access each channel. "SBL" refers to all short-baseline pion decay in-flight neutrino beams.

C. Sterile neutrinos and short-baseline physics

Most models of neutrino mass generation involve right-handed, and hence sterile, neutrinos; however, the mass of those right-handed neutrinos is not well constrained. In principle, the mass scale of the right-handed neutrino can range from sub-eV up to the Planck scale and only a few regions of parameter space have been probed in detail. Thus, the existence of sterile neutrinos with a mass around the eV-scale seems plausible. Experimental results from LSND [198] indicate a $\bar{\nu}_\mu \to \bar{\nu}_e$ flavor conversion at the level of about 0.003. Given the baseline and mean energy of neutrinos in this experiment, oscillation involving a neutrino with a mass squared difference $\Delta m^2 \sim 1\,\mathrm{eV}^2$ is a possible and straightforward explanation. More recently, the MiniBooNE experiment [199, 200] has seen hints of flavor transitions in both $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$, which appear to be consistent with the oscillation interpretation of the LSND result.

Atmospheric neutrino oscillations imply $\Delta m^2_{31} \simeq 2 \times 10^{-3}\,\mathrm{eV}^2$ and solar neutrino oscillations require $\Delta m^2_{21} \simeq 7 \times 10^{-5}\,\mathrm{eV}^2$. Therefore, at least four neutrinos are required to allow for another Δm^2 to be of order eV^2. From the invisible decay-width of the Z-boson it is known that there are only three active, light neutrinos and hence, the extra neutrino to explain LSND and MiniBooNE has to be sterile.

Any oscillation from one active neutrino into another active neutrino mediated by a sterile neutrino requires that the sterile neutrino mixes with both the initial and final active neutrino flavor. As a consequence, any appearance signal, as potentially observed by LSND and MiniBooNE, implies the existence of a corresponding disappearance signal. This correspondence can be made quantitative: the energy-averaged oscillation probabilities obey the following inequality, irrespective of the number of sterile neutrinos,

$$\langle P_{\nu_\mu \to \nu_e} \rangle \leq 4 \left(1 - \langle P_{\nu_\mu \to \nu_\mu} \rangle\right) \left(1 - \langle P_{\nu_e \to \nu_e} \rangle\right) . \tag{9}$$

An analogous expression holds for antineutrinos, noting that the energy-averaged disappearance probabilities for neutrinos and antineutrinos are equal.

Somewhat more recently, the reactor antineutrino anomaly has been pointed out [201] indicating a 6% deficit of $\bar{\nu}_e$ from nuclear reactors at a distance of 10-100 m. Approximately one half of the effect, that is, a deficit of 3%, is due to the re-evaluation of reactor antineutrino fluxes [202], which has been independently confirmed [203]. The error budget of the reactor antineutrino flux calculations is a difficult subject in its own right, due to the not-well-understood impact nuclear structure might have [204] and the fact that recently a feature, the so-called "5 MeV bump", in the measured spectrum of reactor antineutrinos has been found. This feature is not predicted by the flux calculations [202, 203]; for a summary on the 5 MeV bump see Ref. [205]. Taken at face value, the 6% neutrino deficit can be interpreted as disappearance of $\bar{\nu}_e$ at a level and with a Δm^2 consistent with the LSND and MiniBooNE results and their respective interpretation as sterile neutrino oscillation.

Support for an eV-scale neutrino also comes from the radioactive source calibrations of the radiochemical gallium solar neutrino experiments, GALLEX and SAGE. In order to verify the operation of these experiments, electron capture sources based on either chromium-51 [206, 207] or argon-37 [208] were used to expose the detectors to a well known, mono-energetic ν_e flux. The resulting number of germanium atoms stayed below the expectation by about 25% and this result can be interpreted as the disappearance of ν_e with oscillation parameters consistent with the previously mentioned evidence [209].

In combination, these indications have led to a renewed interest in the question of sterile neutrinos at the eV-scale [210] and as a result there is a plethora of newly proposed experiments. At the same time, the fact that no ν_μ disappearance at the relevant value of L/E has been observed and many other searches have produced null results is a source of significant tension in global fits; see for instance Ref. [211]. Also, cosmological observables are sensitive to the presence of a eV-mass sterile neutrino and while some authors claim considerable tension, other authors find acceptable compatibility, *e.g.*, [212]. It appears that cosmology so far remains inconclusive for this problem.

To make any progress on the question of a light sterile neutrino, new experiments are necessary and this has been recognized by the HEP program. Specifically, P5 recommends to perform new beam-based experiments at Fermilab [213]. Conclusively testing the sterile neutrino interpretation will require sharpening of the experimental results on both sides of Eq. 9 by simultaneously pursuing appearance and disappearance searches in both neutrino and antineutrino modes.

Table IX lists all possible oscillation channels and enumerates the experiments which can access a given channel. "SBL" summarizes all possible experiments which can be performed in a pion decay in-flight beam and includes all experiments proposed within the Fermilab short-baseline program. Pion decay in-flight beams contain an intrinsic ν_e component at the level of 1% which is about 3-10 times larger than the expected signal. It appears doubtful whether precision measurements in case of a discovery are possible in this environment. Due to the poorly known primary beam flux, any credible disappearance search will require a near and far detector comparison, which in practice is difficult to achieve at high accuracy because of the different geometric acceptance of the near and far detector. OscSNS [214] is the proposal for an experiment exploiting neutrinos from pion decay-at-rest at Spallation Neutron Source at Oak Ridge National Laboratory. OscSNS would use the same process to generate and to detect neutrinos as LSND did, at the same energy and baseline. This constitutes the most direct test possible of the original LSND result.

Atmospheric neutrinos already provide stringent limits on ν_μ and $\bar{\nu}_\mu$ disappearance and new experiments like low-energy extensions of IceCube, see for instance [215], as well as the ICAL detector at the Indian Neutrino Observatory, are expected to significantly improve these limits.

SOX is the proposal to deploy radioactive sources under the Borexino detector [216]; currently two different types of source are considered. One possibility is a 10 MCi exposure to a chromium-51 source, which provides a mono-energetic low-energy ν_e flux detected by elastic ν-e scattering. Another possibility is a 75 kCi cerium-144 source, which provides a relatively high-energy beta-spectrum type flux of $\bar{\nu}_e$, detected by inverse beta decay. The cerium source is pursued as an entirely European project and data taking may already start by the end of 2015, whereas the chromium source would profit from U.S. involvement, specifically irradation of chromium-50 in the High-Flux Reactor (HIFR) at Oak Ridge. Both sources are too low in energy to allow for appearance searches and thus, this would constitute a disappearance search in the electron channel.

IsoDAR [217] is also exploiting beta decay as its neutrino source; in this case it is the high-energy beta decay of lithium-8, which is produced online using neutrons from a spallation target driven by a several 100 kW beam of 60 MeV H_2^+ ions. The detection reaction is inverse beta decay and ideally multi-kiloton detectors either based on water or liquid organic scintillator are used.

All source experiments provide a well characterized source flux and spectrum[3]; however the energy of the neutrino is entirely determined by nuclear physics and as a result the accessible L/E-range is limited. The SOX configurations suffer from somewhat limited statistics. For IsoDAR a significant accelerator component is required, which in conjunction with the necessary shielding and decommissioning at the end of the experiment will require a careful assessment of lifetime cost. PROSPECT [218] is one of many proposed reactor short-baseline experiments aimed at directly confronting the reactor antineutrino anomaly. The key is to use the near/far detector concept employed very successfully by Daya Bay and RENO at a much shorter distance— meters instead of hundreds of meters. The resulting challenge lies in dealing with backgrounds from reactor operation and surface deployment. Statistical errors can be made quite small, thanks to the enormous flux of reactor antineutrinos; however the L/E-range is limited by the reactor antineutrino spectrum.

It is quite plausible that a combination of a number of those experiments will be able to provide a conclusive test of the sterile neutrino interpretation of the anomalies listed at the beginning. Most of these experiments will have great difficulties in going beyond a simple yes/no answer; in particular precision studies aimed at discerning the number of sterile neutrinos involved or studying the question of potential CP violation for two or more sterile neutrinos are beyond their reach. In the long run, therefore, an experiment like nuSTORM may become attractive again [219].

In this context, it is noteworthy that many of the proposed experiments, *i.e.*, almost all experiments proposed for facilities outside of Fermilab, have intellectually a close relation to the nuclear physics program. For many experiments the relationship is even closer; for instance PROSPECT and the chromium-51 source experiment both rely on access to HFIR at ORNL. These tight connections imply that some level of coordination between HEP and NP would be desirable.

X. NEW INITIATIVES

A. Dark Photons, hidden sectors, and light dark matter

Dark matter and neutrino mass provide strong empirical evidence for physics beyond the Standard Model (SM). Arguably, rather than suggesting any specific mass scale for new physics, they point to a hidden (or dark) sector,

[3] Maybe with the exception of the cerium-144 source, where a few percent of emitted neutrinos stem from forbidden beta decay branches and hence are subject to considerable nuclear structure effects.

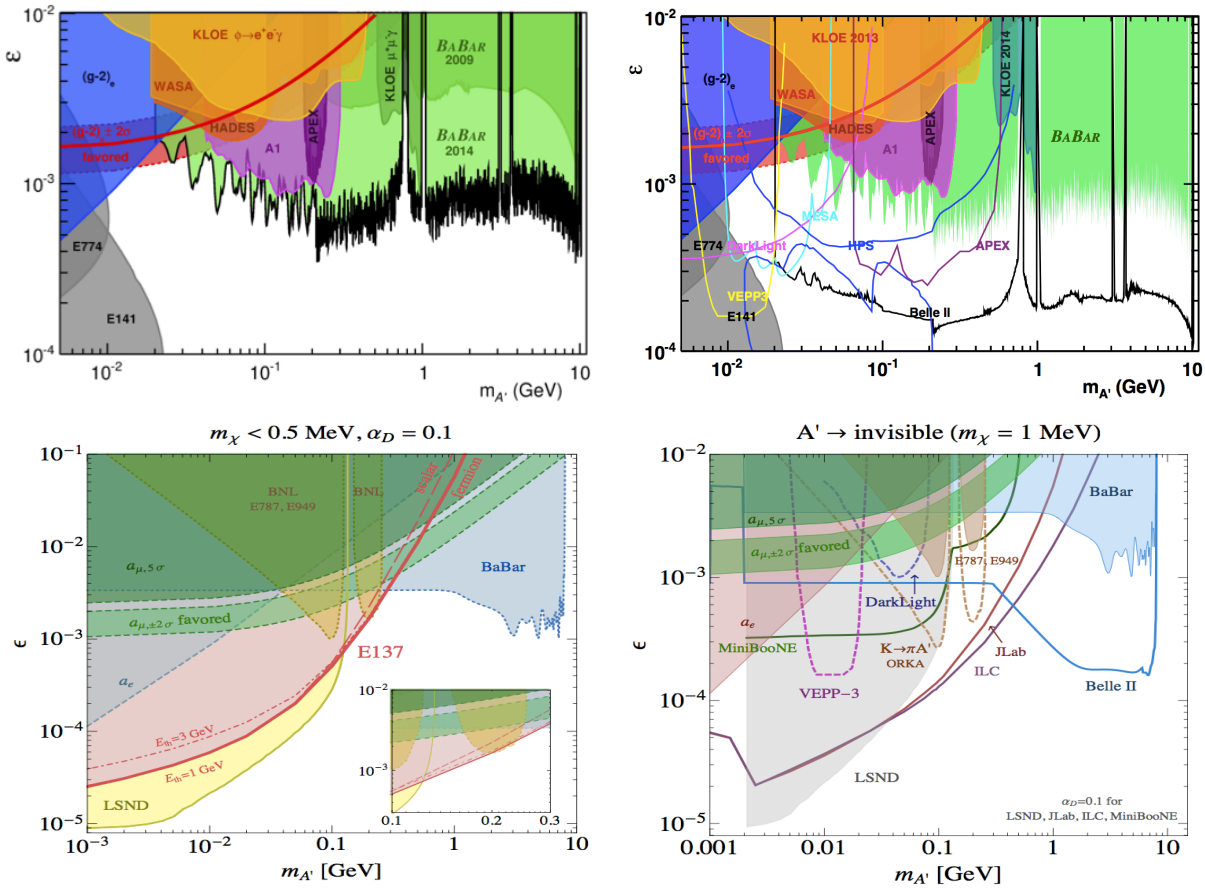

FIG. 16: Constraints (left), and future sensitivity (right) for visible decays [220, 221] (top) and invisible decays [222, 223] (bottom) of a kinetically mixed dark photon. The narrow band in each case defines the region in which vector loops can shift $g-2$ of the muon into agreement with experiment. For the case of hidden decays, the constraints from LSND and E137 further rely on the dominant decay to a metastable state (e.g. light dark matter) which produces a detectable signature through neutral-current-like scattering.

weakly-coupled to the SM. These sectors also arise in many top-down models of beyond the SM [223]. Dark sectors containing light stable degrees of freedom, with mass in the MeV-GeV range, are of particular interest as dark matter candidates as this regime is poorly explored in comparison to the weak scale. Low to medium energy experiments with high precision and/or luminosity are ideally suited to explore this light dark sector landscape.

From a theoretical perspective, it is useful to consider a general parametrization of the interactions between the SM and a hidden or dark sector. A natural assumption is that any light dark sector states are SM gauge singlets. This automatically ensures weak coupling to the visible (SM) sector, while the impact of heavier charged states is incorporated in an effective field theory expansion at or below the weak scale,

$$\mathcal{L} \sim \sum_n \frac{c_n}{\Lambda^n} \mathcal{O}^{(k)}_{\rm SM} \mathcal{O}^{(l)}_{\rm hidden}, \tag{10}$$

where k and l denote operator dimensions and $n = k + l - 4$. The generic production cross section for hidden sector particles then scales as $\sigma \sim E^{2n-2}/\Lambda^{2n}$. Thus lower dimension interactions, unsuppressed by the heavy scale Λ, are preferentially probed at lower energy. Such interactions are natural targets for the intensity frontier more generally. The set of lowest-dimension interactions, or *portals*, which generalizes the right-handed neutrino coupling, is quite compact. Up to dimension five ($n \leq 1$), assuming SM electroweak symmetry breaking, the list of portals includes [223]:

- $\mathcal{L} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$ - dark photons kinetically mixed with hypercharge,
- $\mathcal{L} = (AS + \lambda S^2) H^\dagger H$ - dark scalars coupled to the Higgs,

- $\mathcal{L} = y_N LHN$ - sterile neutrinos coupled via the lepton portal,
- $\mathcal{L} = \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$ - axion-like pseudoscalars coupled to the axial current.

On general grounds, the couplings of these lowest dimension operators are minimally suppressed by any heavy scale, and new weakly-coupled physics would naturally manifest itself first via these portals in any generic top-down model. Thus portals play a primary role in mediating interactions of light dark sector states with the SM.

One of the simplest hidden sectors involves states charged under a new U(1)′ gauge group. The corresponding gauge boson, dubbed the dark photon A'_μ, is kinetically mixed with hypercharge via the vector portal above, which induces a coupling to the electromagnetic current $\mathcal{L} = -\epsilon e A'_\mu J^\mu_{\rm EM}$. This scenario, and variations involving other non-anomalous currents such as $B - L$, provide some of the few relatively unconstrained UV-complete extensions of the SM. Models of this type, with a massive vector, have been the focus of considerable attention in recent years due, for example, to the role the dark vector mediator can play in models of dark matter. Initial interest arose from the utility of light vector mediators in building viable dark matter models to explain the enhanced positron fraction observed in cosmic rays by PAMELA, FERMI and most recently AMS-02. WIMP dark matter annihilating via light mediators is Coulomb-enhanced at the low velocities $v \sim 10^{-3}$ relevant for the galactic halo. Subsequently, these scenarios have been explored within the context of light sub-GeV dark matter, in which dark matter lies in the hidden sector charged under U(1)′, and as the generic interaction channels accessible at low energy according to the operator analysis above. Further, the dark sector has been invoked to explain both the muon g-2 result [224] as well as to understand the proton radius puzzle [225]. Reference [226] explores low energy parity violating electron scattering as a means to constrain dark bosons.

The A' might be produced in a number of ways: radiative production in electron scattering from a nucleus; π^0 decay to $e^+e^-\gamma$; $\Upsilon(2S, 3S) \to \gamma A'$, followed by $A' \to \mu^+\mu^-$; and in $e^+e^- \to \gamma A'$, followed by $A' \to e^+e^-,\ \mu^+\mu^-$. In addition, the A' can decay invisibly. Over the last several years, there has been an intensive worldwide effort to search for evidence of the A'. Ingenious searches have been conducted [222, 227] using data from past experiments completed within the last three decades. In addition, existing experiments built for other scientific purposes have been used to search for the A' [228–234]. At the LHC, the ATLAS [235], CMS, and LHCb experiments are conducting searches for weakly coupled light gauge bosons. At Fermilab, both the MiniBooNE [236] and SeaQuest [237] experiments will search. AT CERN, the SHIP experiment at the SPS is planned [238]. To date, a large area of the coupling $\alpha' \equiv \epsilon^2\alpha_{EM}$ vs. mass ($m_{A'}$) space for A' decay to e^+e^- has been excluded at the 2σ level. No evidence of the A' has been found. Further searches must employ innovative techniques that aim for higher precision in dedicated experiments. A number of nuclear physics facilities are well positioned to mount next-generation searches for the A':

- Dedicated electron fixed-target experiments at JLab, including HPS [239], APEX [228], and DarkLight [240] aim to observe visible decays of the dark photon $V \to l\bar{l}$, or invisible decays to further dark states. BDX aims to test invisible decays by observing neutral-current-like scattering of the hidden decay products (e.g., light dark matter) in a detector downstream of the target.
- Proton fixed-target experiments aiming to observe coherent elastic neutrino-nucleon scattering would also be sensitive to invisible dark photon decays to light dark sector particles that scatter elastically (and likely coherently) in the detector.
- Searches for rare pion or kaon decays (e.g. at NA62) also provide sensitivity to dark photons with various decay channels.

A summary of existing constraints, and several proposals to extend the sensitivity reach, appears in Fig. 1.[4]

B. Theia: A Realization of the Advanced Scintillation Detector Concept

The recent development of Water-based Liquid Scintillator (WbLS), and the concurrent development of high-efficiency and high-precision-timing light sensors, has opened up the possibility for a new kind of large-scale detector capable of a very broad program of physics. Theia is a proposed realization of this Advanced Scintillation Detector Concept (ASDC) that combines the use of WbLS, doping with a number of potential isotopes for a range of physics

[4] Recent preliminary results from NA48/NA62 have excluded the remaining part of the muon $g-2$ band for $m_{A'} \sim 10-30\,$MeV, provided A'_μ only has SM decays via kinetic mixing. See e.g. `http://na48.web.cern.ch/NA48/Welcome/images/talks/mesonnet13/Mesonnet14_Goudzovski.pdf`.

goals, high efficiency and ultra-fast timing photosensors, and a deep underground location. Such a detector at the Long Baseline Neutrino Facility (LBNF) far site could operate in conjunction with the liquid argon tracking detector proposed by the LBNE collaboration. The goal is the deployment of a 30–100 kiloton-scale detector, the basic elements of which are being developed now in experiments such as WATCHMAN, ANNIE, SNO+, and EGADS. The program would include determination of the neutrino mass hierarchy and observation of CP violation with long-baseline neutrinos, searches for proton decay, ultra-precise solar neutrino measurements, geo- and supernova neutrinos including diffuse supernova antineutrinos, and neutrinoless double beta decay. Theia thus aspires to a program than spans physics from MeV to multi-GeV scales.

Theia combines the benefits of both water Cherenkov detection and pure liquid scintillator in a single detector. WbLS uniquely offers the high light yield and low threshold of scintillator with the directionality of a Cherenkov detector [241]. Initial light absorbance measurements promise a long attenuation length, perhaps even close to the attenuation length of pure water at wavelengths above 400 nm, enabling an affordable, large-scale detector. The use of high-sensitivity photomultipliers or high-precision timing measurement devices such as the newly-developed Large Area Picosecond Photo-Detectors (LAPPDs) [242–246] would allow excellent separation of the prompt Cherenkov light from the delayed scintillation, providing a powerful particle identification technique beyond that of either water or pure scintillator detectors. This would significantly increase signal-to-noise ratios across the breadth of the physics program.

WbLS chemistry also allows loading of metallic ions as an additional target for particle detection, including ^{6}Li for short-baseline reactor anomaly studies, ^{7}Li for charged-current solar neutrino detection, ^{nat}Gd for neutron tagging enhancement, or ^{nat}Pb for total-absorption calorimetry or solar neutrino studies. Loading of isotopes that undergo double beta decay would allow Theia to pursue a program of neutrinoless double-beta decay ($0\nu\beta\beta$). Double beta decay isotopes that cannot be loaded in pure scintillator, due to their hydrophilic nature, are accessible with WbLS technology. With the large size and high fractional loading possible, $0\nu\beta\beta$ target masses of tens of tons or more could be achieved with this technique, offering a practical way to push sensitivities to lepton number violation into the normal hierarchy region.

The formula and principle of a mass-produced WbLS have been developed and demonstrated at the BNL Liquid Scintillator Development Facility. Both bench-top measurements and low-intensity proton beams have been utilized at incident energies above and below Cherenkov threshold. Different metal-doped WbLS samples have been produced with high stability (including Li, Gd, Te, Pb, Zr), with loadings of a few tenths to several percent for different experimental requirements, and are continuously monitored at different temperature ranges over time. A further study for prototyping large-scale liquid production and deployment at the ton-scale is in high demand, which would allow a direct measurement of the separation of Cherenkov and scintillation light, and attenuation measurements at longer scales. The instrumentation for large-scale liquid production is still under design. The assembly of a 1-ton WbLS prototype is ongoing and expected to be ready for deployment in 2015. In addition, a large scale ($\sim$3 kT) deployment of WbLS is intended for the second phase of the planned WATCHMAN detector.

In order to realize the physics goals of Theia, a vigorous and forward-looking program of R&D is called for targeting the properties of the WbLS, along with further development of fast-timing solutions and the associated readout electronics. Such a program is already underway, with the goal of developing the WbLS target and associated detector technology for broad physics goals, from long-baseline to low-energy physics. A full technical design and cost estimate is under consideration. Many of the risks and challenges associated with Theia have been addressed in the development of the Technical Design Report for the water Cherenkov detector proposed by the LBNE collaboration [247]. Additional risks are associated with the use of new technology: the WbLS target, and new ultra-fast timing photosensors. WbLS has been well studied on a bench-top scale; the primary risk remaining is in the attenuation length and stability of optical properties over long time periods. These will be addressed with high priority. While the use of new technology such as LAPPDs could significantly enhance performance, the baseline detector design assumes conventional high-QE PMTs, which are well characterized and understood. If LAPPDs or an alternative technology are available and tested prior to construction, then the possible replacement could be of benefit to the physics program. Planned tests of new technologies at various institutions and in the ANNIE and WATCHMAN detectors will be critical steps in the developing R&D program.

Theia offers a unique opportunity to combine conventional neutrino physics with rare-event searches in a single, large-scale detector. Use of the novel and inexpensive WbLS target could signify a breakthrough in background-rejection capability and signal detection efficiency, allowing detectors to be scaled by an order of magnitude or more, which would revolutionize the field. In addition, Theia would have flexibility to adapt to new directions in the scientific program as the field evolves, making it a unique instrument of discovery.

C. Antihydrogen Physics at CERN

Antihydrogen is a pristine system for studies of antimatter–it is the antiparticle of the simplest atom. Differences between the two are forbidden by the well-established Charge, Parity and Time (CPT) invariance principle and Lorentz symmetry. CPT is basic to local relativistic QFT models of physical laws: It requires only Lorentz invariance, locality and spin-statistics. A search for CPT violation may seem futile. However, testing established laws in new areas is a long-standing and often very rewarding tradition in physics, surprising theorists and experimentalists alike. Beginning with Newton's Laws, many well-established laws have been superseded. Antihydrogen experiments are an exploration for unknown physics that, if found, would challenge the foundations of physics. Experimentation on neutral antimatter - antihydrogen atoms - has now reached the point of maturity where precision physics is expected on numerous experiments over the next decade.

Production of antihdyrogen was first achieved in experiments at CERN [248] and FNAL [249], where it was produced at relativistic energies. Cold antihydrogen was synthesized by the ATHENA [250] and ATRAP [251] collaborations in 2002. The ALPHA Collaboration trapped [252] antihydrogen in 2010, and shortly thereafter stored anti-atoms for 1000s [253], induced resonant quantum transitions in antihydrogen with microwaves [254], performed a precision measurement of charge neutrality [255] and measured a coarse bound on the strength of Earth's gravity on antihydrogen dynamics. ATRAP reported trapping antihydrogen[256] and has performed [257] the highest precision antiproton magnetic moment measurements to date; another experiment, BASE [258], is dedicated to measurement of the antiproton magnetic moment.

Antihydrogen experiments are conducted at the CERN Antiproton Decelerator (AD), the world's only facility providing low energy antiprotons. The AD currently supplies antiprotons to six experiments that are operating or approved. These experiments are dedicated to measurements of antihydrogen and properties of antiprotons. The ALPHA, ATRAP, ASACUSA [259], AEGIS [260] and BASE collaborations are already operating. ALPHA utilizes a Penning-Malmberg trap to confine and cool antiprotons and positrons, and mixes the two species in a minimum B-field geometry to trap the resulting antihydrogen. ATRAP is broadly similar, but uses a slightly different magnetic trap geometry and mixing scheme. ASACUSA works to develop antihydrogen hyperfine spectroscopy near zero fields using an antihydrogen beam. This approach is complementary to that of ALPHA and ATRAP, which trap antihydrogen in high magnetic fields. ASACUSA has made significant recent progress, but has yet to observe ground-state antihydrogen. This is needed for precision studies, routinely prepared in the ALPHA trap, and reported by ATRAP as well.

Two collaborations, AEGIS and GBAR [261], intend to focus on gravity studies, using ambitious, but as yet unproven, techniques such as cooling of antiprotons to sub-Kelvin temperatures, production of Stark-accelerated beam of excited antihydrogen (AEGIS); generation, trapping, and cooling of positive antihydrogen ions (with two positrons and one antiproton) followed by photo-neutralization for creation of cold antihydrogen (GBAR). These experiments expect to reach sensitivities of order $10^{-2}g$, where g is the strength of the Earth's gravity. A proposal to build a vertical antihydrogen trap mated to an anti-atom interferometer estimates sensitivity of order $10^{-4} - 10^{-6}g$ [262].

The CERN AD provides 5 MeV antiprotons to users. A new ring is being constructed, ELENA, which will further reduce antiproton energies to 100keV and supply them on demand to experiments. AD users are eagerly awaiting the ELENA, which should allow much higher antiproton trapping efficiencies and enable 24 hour operation. This, along with advances in trapping techniques, such as laser cooling [263], heralds the beginning of precision laser and microwave spectroscopy, and charge neutrality studies, of CPT invariance. As an example of parameters that may be achieved [264] the hyperfine spectroscopy on the new ALPHA apparatus (Fig. 18) could reach 1kHz absolute frequency resolution, corresponding to $< 10^{-6}$ relative precision. Microwave studies of hyperfine splitting probe specific combinations of the Lorentz-violating parameters of the Standard Model extension that are currently unconstrained. [265]. At a special magnetic field of about 0.65 Tesla, the separation energy between the two upper hyperfine states of the trapped anti-atoms has a very broad maximum and operation here is conducive to high precision measurements. (Fig. 17). While antihydrogen 1s-2s spectral measurements are currently far from being able to reach the exquisite precision of atomic hydrogen spectral tests, interesting regimes of comparison may appear [264–267] at the few kHz level. Charge neutrality measurements have been estimated to reach Qe to $10^{-10}e - 10^{-12}e$ precision (where $-e$ is the electron charge) [268], with the better number requiring laser and adiabatic cooling and favorable systematics (Fig. 19).

Participation in antihydrogen and antiproton physics is highly leveraged by ongoing CERN support of the AD, with additional EU and non-US national funding. The AD is the only facility that can currently deliver low energy antiprotons; thus all experiments in this emerging subfield of physics must be located there. The antihydrogen experiments provide an excellent opportunity for agencies to invest in fundamental CPT symmetry tests in a cost-effective manner.

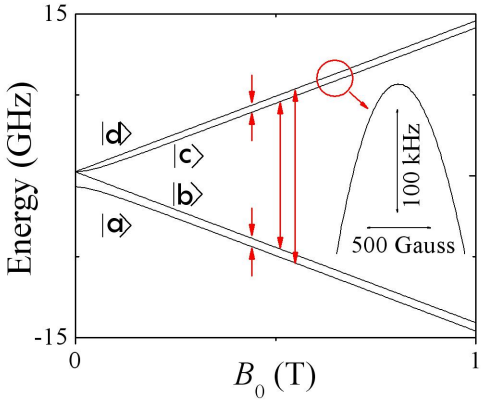

FIG. 17: Breit-Rabi Diagram showing hyperfine lines and the quadratic dependence of frequency with B_0 near the maximum of the *c*-*d* splitting. Hyperfine spectroscopy experiments are planned at ALPHA2 at a magnetic field 0.65 T, where the separation energy between the two upper hyperfine states has a broad maximum as a function of field strength [269].

D. Measuring the Neutrino Mass Hierarchy with Atmospheric Neutrinos

(For the IceCube/PINGU Collaboration, http://icecube.wisc.edu/collaboration/authors/pingu)

The neutrino mass hierarchy is one of the key remaining unknowns in the neutrino sector, with important implications for a number of nuclear physics problems, including neutrinoless double beta decay ($0\nu\beta\beta$) and the physics of supernova explosions. $0\nu\beta\beta$ in particular is a key focus of neutrino research in nuclear physics [270].

The relationship between the effective mass for $0\nu\beta\beta$and the mass of the lightest neutrino depends on whether the mass hierarchy is normal or inverted. If the mass hierarchy is inverted, then there is a minimum effective mass which could be reached by envisioned next-generation neutrinoless double beta decay experiments. If there were an independent measurement of the mass hierarchy, an experiment that reached this limit could conclusively state that neutrinos are not Majorana particles. If the mass hierarchy is normal or unknown, then no such statement is possible. Experiments could observe $0\nu\beta\beta$, but, in the absence of an observation, the nature of neutrinos would remain uncertain.

Directly measuring the neutrino mass hierarchy requires high-resolution measurements of neutrino oscillations. There are a number of proposed methods to do this [271]. The least costly and possibly fastest approach is to use atmospheric neutrinos. Three groups are proposing this: PINGU (Precision IceCube Next Generation Upgrade) in the Antarctic ice cap, ORCA (Oscillation Research with Cosmics in the Abyss) in the Mediterranean Sea [272], and the India-based Neutrino Observatory [273]. Here, we focus on PINGU, which has a large U. S. participation.

PINGU will permit a determination of the mass hierarchy, independent of the CP violation parameter, at relatively modest expense, using a well-understood technique with minimal risk, on a short time scale. It will leverage the knowledge gained in designing, deploying and operating IceCube and its in-fill array DeepCore. IceCube and DeepCore have been continuously taking high-quality physics data since early 2011. By deploying PINGU within and around existing IceCube and DeepCore digital optical modules (DOMs), a multi-megaton fiducial volume of ice would be instrumented with sufficient photocathode density to yield a neutrino energy threshold of a few GeV. The scale of PINGU would permit measurement of the oscillations of atmospheric neutrinos over a range of energies and a variety of baselines (up to the diameter of the Earth) with sufficient precision that hierarchy-dependent distortions of the oscillations due to the presence of matter could be observed. PINGU will also provide a precise measurement of θ_{23}.

PINGU construction and technology would be similar to that used in IceCube, with large photomultiplier tubes and readout electronics encased in pressure vessels embedded in the Antarctic ice cap below the US Amundsen-Scott South Pole Station. The 2850 m thick, very transparent South Pole ice cap would serve simultaneously as neutrino target, Cherenkov medium, and detector support structure.

A likely construction scenario places PINGU under the umbrella of an expanded IceCube-based facility at the South Pole. PINGU would be constructed first, followed by an extension focused on high energy astrophysical neutrinos, obtaining economies of scale through the use of common hardware and installation techniques. The PINGU share of the facility cost is roughly \$55M (US cost, including contingency) plus \$25M (foreign contribution) for a total of \$80M. Detector construction can be completed five years after funding starts, or as early as 2020. The determination of the mass hierarchy at the 3σ level would be possible with about 3 years of data.

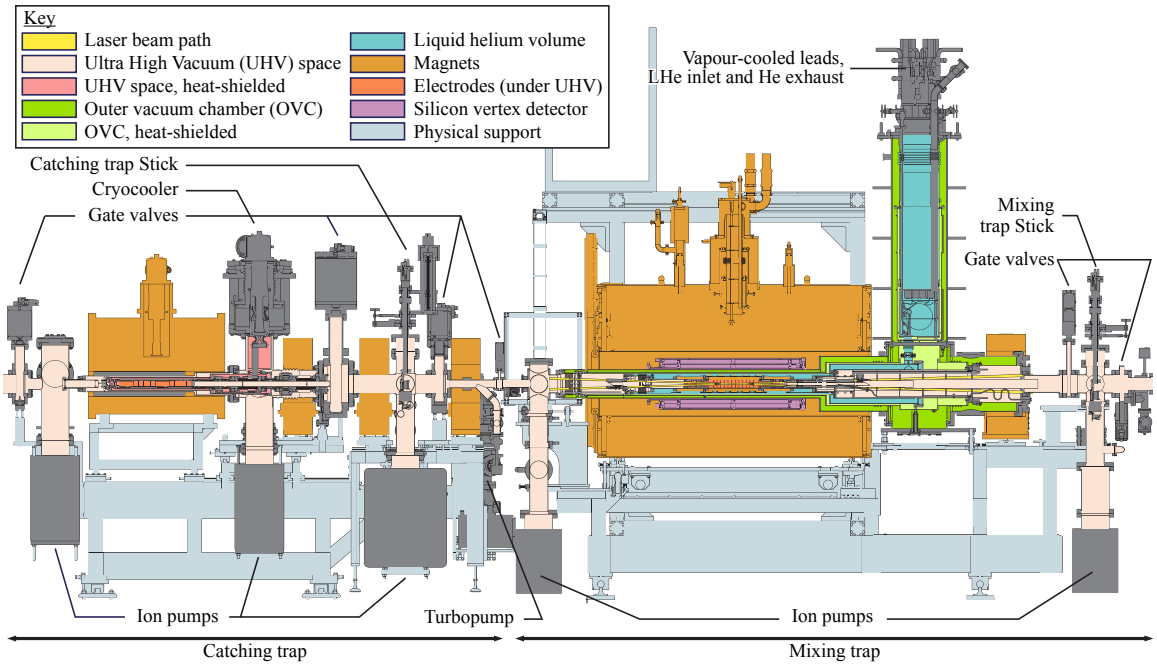

FIG. 18: ALPHA2 Antihydrogen trap schematic

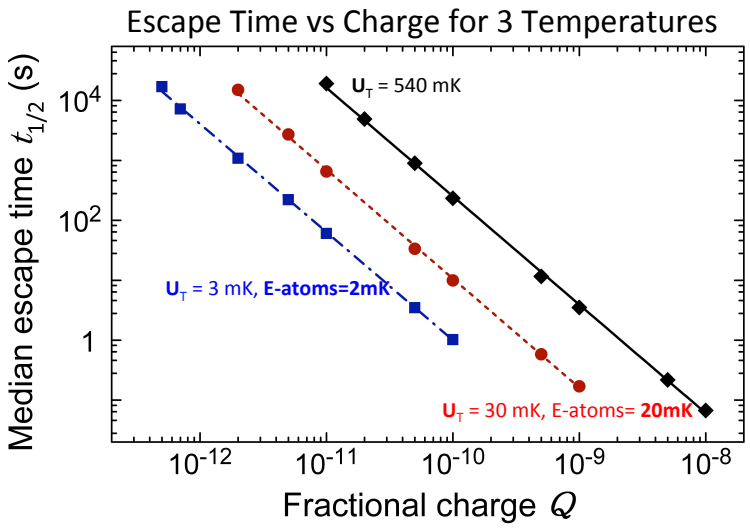

FIG. 19: Simulated escape time and charge sensitivity for different temperatures for possible antihydrogen charge neutrality experiments. The trapping parameters for the black curve were reached by ALPHA. The red assumes laser cooling and blue further assumes adiabatic cooling. Systematic effects come into play at high sensitivity and will be studied. From Ref. 268

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A determination of the neutrino mass hierarchy would contribute to advances in a number of other areas in the nuclear physics purview. Knowing the neutrino mass hierarchy is also important for understanding how supernovae explode; neutrinos interact collectively with the matter in supernovae, and the character of these interactions depends on the hierarchy. These differences are important in modelling supernovae [274] and understanding heavy-element production in the universe, and they also have observational consequences [275]. An independent determination of the neutrino mass hierarchy would allow future observations of neutrinos from supernovae to be used to much better pin down other aspects of the supernova explosion process.

PINGU will also become one of a handful of active supernova neutrino detectors. Its multi-megaton fiducial volume gives it the ability to observe galactic supernova with unprecedented (millisecond) time resolution [276], and it will have a phototube density high enough to determine both the integrated neutrino luminosity and the neutrino energy spectrum on short time scales [277].

In conclusion, PINGU offers an extremely cost effective way to provide answers to the key (and still relevant) question posed in the 2007 Nuclear Science Long Range Plan [278], "What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?" PINGU will use atmospheric neutrinos to determine the neutrino mass hierarchy, with a direct impact on the interpretation of $0\nu\beta\beta$ measurements, the modelling and understanding of supernova explosions, and the detector will serve as a premier supernova neutrino detector in its own right.

E. Non-Newtonian gravity, long–range forces

Many theoretical models of the most profound unexplained phenomena in physics predict forces of nature beyond gravity and electromagnetism at sub-millimeter length scales. String theory contains extra dimensions of spacetime that could modify gravity [279] and also contains particles that would mediate forces much stronger than gravity at these scales [280]. Several theories to explain dark matter and dark energy also produce new weakly coupled long-range interactions [281]. The fact that the dark energy density of order $(1\ \mathrm{meV})^4$ corresponds to a length scale of 100 μm also encourages searches for new phenomena near this scale. Many extensions to the Standard Model contain extended symmetries which, when broken at high energy, lead to weakly-coupled light particles that could constitute dark matter. A general study of interactions between nonrelativistic fermions reveals 16 different operator structures involving the spins and momenta of the fermions [282], and has been used as a convenient, model–independent framework for expressing experimental results. The inverse square law of gravity has not been verified below 50 microns and there could be forces of nature millions of times stronger than gravity acting at that range [283–286]. Searches for sub-millimeter macroscopic forces have advanced rapidly over the last decade. This section reviews this progress as well as the challenges and opportunities for new searches in regimes where nuclear techniques have unique sensitivity.

Mass–coupled interactions: The sensitivity demands for mass–coupled force searches below 1 mm rapidly escalate as the size of the apparatus decreases. Force sensitivities of order 1 fN or below are required near this scale. The size of background forces also increases rapidly in this regime. The Casimir force, which scales as r^{-4}, dominates other interactions at 1 micron and cannot be shielded below about 100 nm, making experiments with macroscopic test masses very challenging. Experiments using atoms are similarly limited by the Casimir–Polder effect, which scales as the electric polarizability. These considerations make neutrons, which are uncharged and have an electric polarizability nearly 20 orders of magnitude smaller than atoms, very attractive probes for mass–coupled forces below 1 micron.

Neutron scattering and interferometry: The best experimental limits on mass-coupled forces with ranges from pm to nm derive from low–energy neutron scattering experiments, the sensitivity of which is limited by the knowledge of the neutron-electron scattering length (b_{ne}). Nesvizhevsky *et al.* analyze a variety of measurements to derive a conservative upper limit on the uncertainty of b_{ne}, and thus constrain new physics [287]. The results, shown in Fig. 20, are still about three orders of magnitude above the specific prediction of a new U(1) gauge boson [288].

Gravity Resonance Spectroscopy: The chameleon mechanism is a way to "shield" certain dark–energy scalar field models from laboratory constraints on macroscopic forces. In this model, a non-linear self–interaction term is added to the dark energy scalar potential, resulting in a strong cutoff of the interaction range in the presence of matter. The current best bound on "strongly–coupled" chameleons comes from the Gravity Resonance Spectroscopy experiment at ILL, from precision measurement of the frequencies of transitions between the bound states of ultracold neutrons in the gravitational field of the earth [299].

Outlook: Prospects for neutron experiments more sensitive to massive scalars must address uncertainties from b_{ne}. Two proposals for small–angle neutron scattering experiments on noble gas targets offer several handles on b_{ne} [293, 294], but the projected improvement is only about an order of magnitude in the range near 1 nm. A proposed neutron charge radius measurement at NIST using neutron interferometry can offer much greater sensitivity [300].

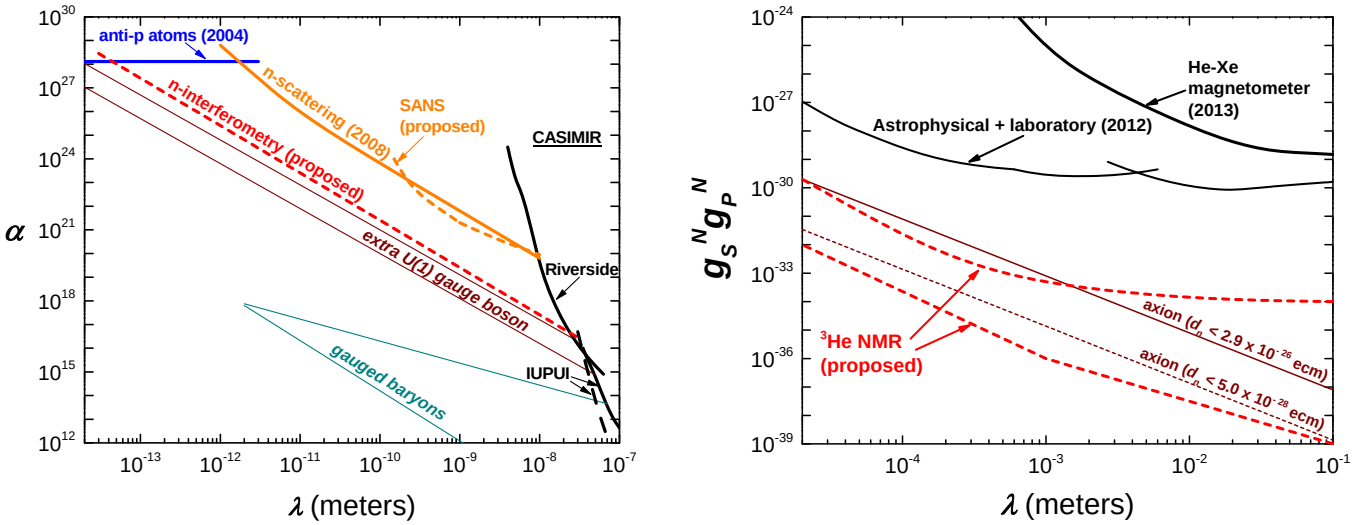

FIG. 20: *Left:* Parameter space for macroscopic mass-coupled forces in which the strength α relative to gravity is plotted versus the range λ. Bold, solid lines are current experimental limits, including those from neutron scattering experiments [287], which span the space between limits from Casimir force experiments with macroscopic test masses [289, 290] (the result from the recent preprint [291] is shown as the dashed line), and from microscopic systems with anti–protonic atoms [292]. Dotted lines are projected limits from proposed experiments including small-angle neutron scattering from noble gas targets [293, 294] and neutron interferometry [295]. Fine lines are theoretical predictions [280]. *Right:* Parameter space for the $\hat{\sigma} \cdot \hat{r}$ "monopole–dipole" interaction between nucleons (adapted from [296]), where the product $g_S g_P$ measures the strength relative to the strong interaction ($\alpha_s \sim 1$). The experimental bounds are defined by magnetometers [297], and the astrophysical + laboratory bounds are derived in [298]. The upper limit on the axion derives from the current constraint on the neutron electric dipole moment d_n [74]; the lower dotted line shows the result of the projected improvements on d_n [95]. The bold dotted lines are the projected limits of a proposed direct search using ^{3}He NMR [296].

This technique can be extended to macroscopic force searches, for which the projected limit covers ten additional square decades of the parameter space for mass–coupled interactions in the range below 1 nm [295]. Much greater sensitivity above 1 nm is possible if a parametric resonance enhancement technique can be realized [301]. Another neutron interferometer experiment has been proposed with two orders of magnitude greater sensitivity to chameleon scalar fields than the current upper limit [302].

Spin–coupled interactions: For forces that depend on the spin of one or both of the test objects, the experimental limits are rather weak. Condensed matter systems with large nuclear polarization are not easy to arrange without an environment that includes high magnetic fields, which can produce large systematic effects in delicate experiments. Limits on P-odd and T-odd "monopole–dipole" interactions between nucleons in the range near 1 mm are shown in Fig. 20. The polarized electrons or nucleons in most experiments employing macroscopic amounts of polarized matter typically possess $\langle p \rangle = 0$ in the lab frame, thus, laboratory constraints on macroscopic forces which depend on both spin and relative momentum are even weaker than for static interactions.

Static sources: The sensitivity attainable in NMR–type experiments helps make up for the weak signals available from practical spin sources. The best direct limits on static monopole–dipole interactions between nucleons derive from NMR measurements on polarized gas samples in close proximity to a dense non-magnetic source mass. The most sensitive existing experiment in the millimeter range measures the relative precession of He–Xe comagnetometers in phase with the modulation of an adjacent bismuth germanate crystal [297]; the polarized nucleons in the magnetometer are the source of the pseudoscalar coupling g_P in the product $g_S g_P$ to which the experiment is sensitive.

More stringent limits than those set by laboratory experiments alone can be obtained with extra assumptions. Fig. 20 shows the results obtained from combining the constraints on g_P from the inferred cooling rate of SN1987A with the constraints on g_S from short–range torsion pendulums with unpolarized test masses [298]. Also shown is the more stringent indirect constraint on $g_S g_P$ obtained from experimental limits on the electric dipole moment of the neutron (d_n) [74], which set bounds on g_S via the QCD θ–term [303, 304]. These limits are often presented as *predictions* for the axion, a light pseudoscalar postulated to explain the strong CP problem of QCD.

Velocity–dependent interactions: Polarized slow neutrons are an especially sensitive probe for macroscopic interactions which involve both the spin and relative momentum. Slow neutrons can be formed into beams with very high polarization by exploiting the spin dependence of the strong and electromagnetic interactions and their pos-

sible interference in crystals, polarized targets, and neutron mirrors with magnetized coatings [305, 306]. Sensitive interferometric measurements can be conducted in various ways by exploiting the neutron's spin degree of freedom.

The best limits on the velocity–dependent monopole–dipole interaction between nucleons derives from an experiment at the Paul Scherrer Institute [307]. This experiment used Ramsey's technique of separated oscillatory fields to compare the precession rate of polarized cold neutrons in a beam passing in close proximity to a polished copper plate with the precession of neutrons in a reference beam.

Outlook: An improvement on d_n by two orders of magnitude would, in the absence of a discovery, translate into a corresponding improvement in $g_S g_P$. However, for a generic light scalar unrelated to the strong CP problem, present bounds from direct searches are more stringent than those inferred from EDM limits for the interaction ranges explored by macroscopic force experiments. Thus, correlating observations in EDM and macroscopic experiments could help distinguish axions from more generic light scalars [308].

A new direct search has been proposed using NMR to detect the induced magnetization of a sample of polarized ^{3}He gas in close proximity to a massive source modulated at the Larmor frequency of the ^{3}He sample [296]. The resulting resonant enhancement of the signal yields a potential sensitivity even greater that the EDM limits, as shown in Fig. 20. A proposed experiment by the NSR collaboration, using slow neutron spin rotation, expects to improve the sensitivity to velocity–dependent monopole–dipole interactions in the millimeter range by up to seven orders of magnitude [309]. This technique has already been used to set the most stringent limits on possible parity-odd interactions of the neutron below 1 mm [310] and on parity-odd components of "in-matter" gravitational torsion [311].

Conclusions: There is great theoretical interest in macroscopic forces beyond gravity with weak coupling to matter. They arise in many models with dark matter, dark energy, and unification models with extra dimensions and extended symmetries. Precision nuclear physics experiments have set the best limits on mass–coupled forces in the range below 1 nm, and on many spin–coupled forces in the range below 1 mm. Many of these limits were established after the publication of the last long range plan, and there are proposals using extensions of the same techniques with several orders of magnitude greater sensitivity in the near future.

F. An Experiment to Measure Neutron-Antineutron Oscillations Using Free Neutrons at the European Spallation Source

During the writing period for the nuclear physics long range plan, an opportunity has emerged for US high energy and nuclear physics groups to play a leading role in a neutron-antineutron oscillation experiment at the European Spallation Source, with over a factor of 1000 increase in sensitivity (over previous free neutron experiments) to search for antineutrons resulting from new physics which violates baryon number. A sensitive search for neutron-antineutron oscillations can provide a unique probe of some of the central questions for particle physics and cosmology: the energy scale and mechanism for baryon number violation, the origin of the baryon-antibaryon asymmetry of the universe and the mechanism for neutrino mass generation. Proton decay, an obvious candidate for baryon number violation studies, violates baryon number by 1 unit, $\Delta B = 1$, and probes very high energy scales ($\sim 10^{15}$ GeV). Neutron-antineutron oscillations, on the other hand, violate baryon number by 2 units, can take place even if proton decay is absent, and can be induced by new physics at energy scales down to a few TeV. In fact, some models which predict oscillations predict measurable signatures (due to colored scalars) within the reach of the Large Hadron Collider. These models also can imply observable static electric dipole moments larger than predicted by the Standard Model. Neutron-antineutron oscillations provide an experimentally accessible window on a variety of sources of new physics at low energy scales, such as theories with extra spatial dimensions and viable models for baryogenesis at or below the electroweak symmetry-breaking scale. The $\Delta B = 2$ selection rules relate oscillations to Majorana neutrino mass generation in models which unify quarks and leptons, providing another window on the origin of neutrino mass (see ref. [312] for more details on the motivation and the approach to a modern neutron-antineutron experiment with free neutrons).

There is interest in the nuclear physics community to participate in research and development during the current planning period to assess the sensitivity and cost of an experiment hosted at the European Spallation Source (ESS)[313]. The primary sources of gain come from coupling a high intensity cold neutron beam to a large neutron reflector. Such an experiment sited at the ESS will provide a factor of 100 more integrated cold neutron flux to an annihilation target than previous free neutron experiments. Other sources of gain derive from a longer free neutron flight path and longer running times than previous experiments. Although all of the technology required for these enormous gains is already available, research and development is required to explore how to minimize the cost associated with achieving the targeted improvement in sensitivity.

XI. NUCLEAR AND NEUTRINO ASTROPHYSICS

Nuclear and neutrino astrophysics has become an increasingly important component of nuclear physics, helping motivate new nuclear physics facilities like FRIB, while also creating rich intersections with other subfields interested in the subatomic physics of the universe. Three Nobel Prizes connected to nuclear physics – the development of solar neutrino astronomy (Davis), the origin of the elements (Fowler), and the nuclear physics of stellar hydrogen burning (Bethe) – originated from nuclear astrophysics. The rapid advance of observational capabilities, examples of which include

- massive underground detectors for observing solar and supernova neutrinos, over their full spectra;
- more precise measurements of abundances from the r-process, preserved in the mantles of some of the galaxy's first stars, and from the Big Bang;
- binary millisecond pulsar observations that have established the existence of 2-solar-mass neutron stars;
- the observation of ultra-high-energy hadronic cosmic ray collisions up to the GZK cutoff, providing data on nuclear collisions at nucleon-pair center-of-mass energies of up to $\sqrt{s} \sim 300$ TeV; and
- new instruments capable of detecting the gamma ray emission and near-infra-red afterglows associated with explosive nucleosynthesis of radioactive nuclei.

are opening up opportunities for major discoveries, while demanding a better understand of the nuclear microphysics governing astrophysical objects. New horizons are clear. With solar neutrinos we can now make precise checks of the thermal stability of the Sun and metal content of its core. The observation of a core-collapse supernova in our galaxy would allow us to test aspects of neutrino oscillations not observable in the laboratory, and could help us resolve the neutrino hierarchy problem. The high-density equation of state important to neutron star structure and to supernovae may soon be probed in much greater detail by Advanced LIGO, as it records the gravitational wave forms produced in neutron star mergers. The combination of FRIB data and rapid advances in observation will require us to develop better tools for modeling the environments where explosive nucleosynthesis occurs: the r-process path must be defined before we will know which laboratory data are most relevant. We will be aided in this endeavor by the next generation of extremely large telescopes and orbiting observatories, which will provide invaluable data on galactic chemical evolution and possibly yield a direct observation of the r-process site. In one of the central problems in physics - identifying the dark matter that dominates our universe - nuclear physics is needed to characterize and compute the possible nuclear responses in direct-detection experiments, and to interpret critically possible indirect astrophysical signals from decaying or annihilating dark matter.

This chapter highlights recent accomplishments of the field and the opportunities for further advancing nuclear and neutrino astrophysics.

A. Solar Neutrinos

Solar neutrinos provide a wealth of opportunities for studying a range of physics, from neutrino properties, to star and solar system formation, to a sensitive search for new physics.

Solar Metallicity The speed of sound predicted by the Standard Solar Model (SSM) is dependent on solar dynamics and opacity, which are affected by the Sun's composition. Sophisticated models of the solar atmosphere developed in recent years [314] result in a ∼30% lower abundance of metals (elements heavier than H or He) in the photosphere relative to previous models. When input into the SSM, this produces a discrepancy in the speed of sound with helioseismological observations, which are sensitive to the composition of the Sun's interior. This "Solar Metallicity Problem" [315, 316] has led to speculations that the Sun's surface might have been altered by the formation of the planets, which swept large quantities of metal from the gas that the Sun accreted. This process, occurring in the late stages of solar formation, could have produced a convective zone depleted in metals, relative to the primordial gas in the Sun's radiative core, violating a key but largely untested assumption of the SSM. The only direct way to measure the metallicity of the solar core and thus test this hypothesis is by observation of neutrinos from the sub-dominant CNO cycle, whose flux is linearly dependent on core metallicity. Further, if both of the major CNO neutrino fluxes, from ^{13}N and ^{15}O beta decay, could be measured, the separate primordial abundances of C and N [317] could be determined, testing the extent to which CNO equilibrium has been reached in the core. More generally, a measurement of CNO neutrinos would test our fundamental understanding of heavier main-sequence stars, which derive most of their energy from the CNO cycle.

Solar Luminosity The so-called luminosity constraint is a manifestation of the assumption that solar neutrinos are produced in the same fusion reactions that power the Sun. A precision measurement of the total solar neutrino flux would test this constraint, and be sensitive to additional mechanisms for energy loss or generation in the Sun. This would also allow us to monitor the stability of the Sun's output over recent years using neutrinos. Such a test requires a percent-level measurement of the pp solar neutrino flux.

Matter Interactions and New Physics The interactions of neutrinos with matter (the "MSW effect [318, 319]") plays a critical role in solar neutrino oscillations, causing an additional suppression of the electron neutrino survival probability from the vacuum oscillation value of a little over one half, to closer to one third above ∼5 MeV. The transition region between the vacuum- and matter-dominated regimes is extremely sensitive to new physics effects, such as sterile neutrinos, mass-varying neutrinos, flavor-changing neutral current and other non-standard interactions. A precision probe of this region is required both to test our understanding of the MSW effect and to search for potential new physics. The neutrinos most sensitive to these effects are ^{8}B neutrinos, because they are produced closest into the core of the Sun. Existing data from the Sudbury Neutrino Observatory (SNO) [320, 321], Borexino [322], Super-Kamiokande [323, 324], and KamLAND [325] show hints at possible new physics at the 2σ level when analyzed together [326], but increased precision is required.

The MSW effect also predicts some regeneration of electron neutrinos as they pass through the Earth. This would result in an asymmetry in the measured flux between day-time and night-time observations. The predicted effect is very small and results to date are limited by statistics. Data from Super-Kamiokande shows a strong hint of this effect at 2.7σ [327], but a definitive observation requires an increased global data set. This is a requirement in order to confirm our understanding of the MSW effect, and the interactions of neutrinos with matter.

Experimental Program A future program in solar neutrinos will need to meet a broad set of requirements, perhaps difficult to achieve in one experiment. Several experiments sensitive to different regimes of solar neutrino oscillation may be needed to cover the breadth of the program, a feat that may be achievable due to the multi-purpose nature of many of these experiments.

Large-scale water Cherenkov experiments, such as Super-Kamiokande and the proposed Hyper-Kamiokande project [328] can collect impressively large datasets, thus have perhaps the best sensitivity to statistics-limited effects such as the day-night asymmetry. However, these experiments are limited in threshold due to the light yield of Cherenkov light.

Organic liquid scintillator (LS) detectors can achieve lower thresholds and improved resolution due to the ~ 50 times higher light yield, and can be made extremely clean. Borexino is a 300t detector in Gran Sasso, Italy, which is operated with unprecedented low levels of contamination in the LS: the intrinsic contamination from ^{232}Th has been reduced to less than 1×10^{-18} g/g, and less than 8×10^{-20} g/g of ^{238}U. As a result Borexino have achieved an impressive suite of solar neutrino results, including the highest precision measurement of ^{7}Be neutrinos [60], the tightest constraint (upper bound) on CNO neutrinos to date [61], first evidence of pep neutrinos [61], and, perhaps most impressive, the first direct measurement of pp neutrinos [62]. The precision at Borexino is limited by two factors: size, and depth (which determines the rate of cosmogenic backgrounds). A large, deep LS detector could address both CNO and pp neutrinos with high precision. SNO+ is a 780t detector in SNOLAB, Canada, which will operate in a pure LS phase prior to loading ^{130}Te for a $0\nu\beta\beta$ search. If SNO+ can achieve the same low levels of radioactive background as Borexino, then the larger detector and low cosmogenic background will allow for better than 10% (5%) precision on the pep neutrinos with 1 (3) years of data, a ∼15% measurement of the CNO flux, and an extraction of the ES spectrum of recoil electrons from low-energy ^{8}B neutrino interactions. LENA is a proposed 50kt detector in Europe, which would achieve unprecedented statistics at low energy [329].

Inorganic scintillator detectors, such as those used for direct dark matter searches, provide the potential for high-precision measurement of pp neutrinos due to the ultra-low thresholds, and the absence of the dominant background in organic scintillator detectors: ^{14}C. Use of liquid neon could provide a background-free fiducial volume due to its lack of long-lived radioactive isotopes, combined with a high-level of pulse-shape discrimination. A 100-ton scale detector, such as the proposed CLEAN experiment [330, 331] could achieve percent-level precision on a measurement of the pp solar neutrino flux. Xenon may also allow a measurements, although would require depletion of ^{136}Xe by a factor of at least 100 due to the high-rate two-neutrino double beta decay background.

Charged-current (CC) detection provides the potential for a high-precision spectral measurement. LENS [332] proposes to employ a segmented detector design to discriminate external backgrounds and use the CC interaction of neutrinos on ^{115}In, which gives a triple coincidence signal, providing excellent background rejection. A 10-ton LENS detector could perform a 2.5%-level measurement of the pp-neutrino flux with 5 years of data. Theia (a realization of the Advanced Scintillation Detector Concept; see Sec. X B) is a proposed large-scale detector with a water-based liquid scintillator [333] target and high photocathode coverage using ultra-fast, high efficiency photon detectors [334]. Theia would provide unprecedented sensitivity to solar neutrinos via two channels: huge statistics for elastic scattering events

at low energy; and potential charged-current detection via isotope loading e.g. ^{7}Li [335]. The unique advantage of THEIA would be the access to directional information for ES events in a low-threshold detector, providing a powerful tool for background discrimination, in addition to a high-precision spectral measurement using CC events. This could allow both a precision measurement of the ^{8}B spectrum, thus providing a sensitive search for new physics, and a measurement of the CNO neutrino flux, including potential sensitivity to the individual components of this flux.

The solar program relies on a number of critical inputs. These include nuclear cross section measurements, such as ^{3}He(α, γ)^{7}Be, ^{7}Be(p, γ)^{8}B, and ^{14}N(p, γ)^{15}O, from experiments such as LUNA [336]. Terrestrial oscillation parameter measurements from experiments such as KamLAND, JUNO [337], and the proposed GADZOOKS! [338] detector can help to constrain global fits, increasing the sensitivity of such fits to potential non-standard interactions and new physics effects.

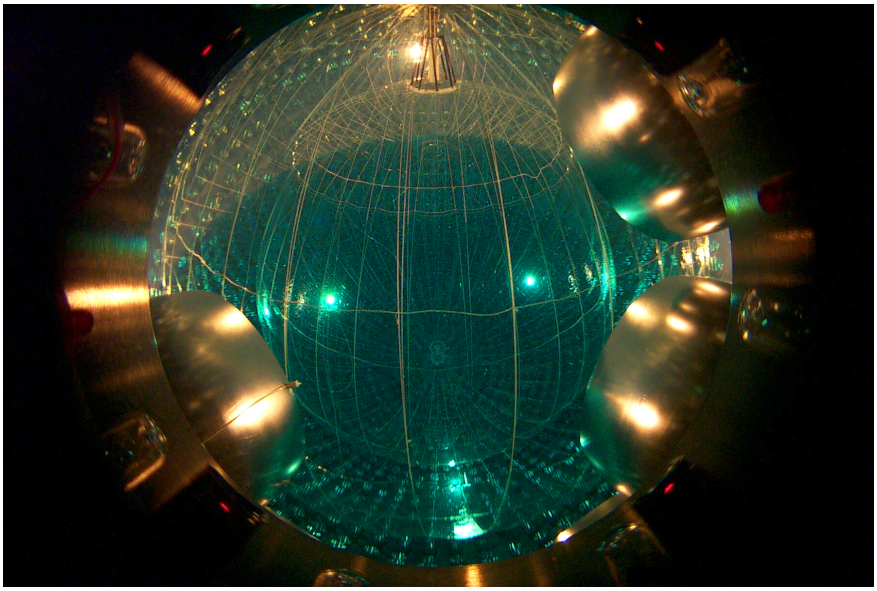

FIG. 21: The Borexino solar neutrino detector, with water being displaced by scintillator in the initial filling of the detector's nylon vessels. The view is from a camera mounted on the surrounding stainless steel sphere, looking out between light cones. Borexino recently announced the first direction detection of the pp neutrinos, produced in the reaction that initiates hydrogen burning in the Sun. Courtesy of the Borexino collaboration.

B. Supernovae, Neutrinos, and Associated Nucleosynthesis

The supernova core-collapse environment represents a promising weak interaction and neutrino physics laboratory, one complementary to terrestrial experiments like LBNF and neutrino-less double beta decay experiments. Weak interactions dominate almost every aspect of the evolution of massive stars, the collapse of their cores to neutron stars or black holes, and much of the nucleosynthesis associated with supernova explosions.

On a timescale of millions of years, massive stars evolve from hydrogen burning through a series of fusion reactions, ultimately producing Chandrasekhar mass cores ($\sim 1.4\,\mathrm{M}_\odot$) composed of iron peak nuclei in nuclear statistical equilibrium and supported by relativistically degenerate electrons. In the run-up to this end state, electron capture, positron decay, and other processes produce neutrinos which stream out of the star and remove entropy. The result is a thermodynamically cold core, trembling on the verge of instability. This core begins to collapse and, in about $\sim 1\,\mathrm{s}$, reaches nuclear density. When the collapse is halted by nuclear forces a "bounce" shock is formed. The shock moves out through the outer core material and weakens. But, aided by subsequent neutrino heating and convective energy transport above the proto-neutron star, the shocks is revived and engineers an explosion and the ejection of nucleosynthesis products. The gravitational binding energy released in the collapse event, $\sim 10\%$ of the core's rest mass, goes into the production of $\sim 10^{58}$ neutrinos of all flavors. These neutrinos diffuse inside the proto-neutron star and more or less freely stream through the mantle above it.

The neutrino bursts associated with core-collapse supernovae (SNe) are among the most interesting sources of neutrinos in astrophysics [339–344]. Neutron star mergers stemming from binary neutron star in-spiral, the gravitational radiation signals from which are key targets for Advanced LIGO, are in broad brush similar to core-collapse super-

novae when it comes to neutrino physics — neutrinos from hot nuclear matter carry away most of the gravitational binding energy released in these cataclysmic events.

Tantalizingly, low entropy and extreme degeneracy of the electrons and huge neutrino fluxes render the physics of stellar collapse and associated environments exquisitely sensitive to lepton number violating processes.

Detection of the burst of neutrinos accompanying the collapse event enables us to unlock this neutrino physics, nuclear physics, and astrophysics lab. In fact, the neutrino burst detected from SN1987a was a watershed event in the history of physics, confirming the collapse-to-neutron star picture given above. The neutrino burst carries information on key parameters in the collapse, *e.g.,* neutron star binding energies, the physics of neutrino propagation in dense nuclear matter, and potentially even information on exotic nuclear phase transitions. Detection of the burst provides a warning of the impending optical display when the shock heats the stellar envelope $\sim 10^3 - 10^5$ s after core collapse (depending on progenitor type). In the addition to bursts we can detect from supernovae within our galaxy, supernovae over cosmological times have produced a diffuse neutrino background that could provide information on the entire history of massive star formation.

Supernova Neutrino Flavor Physics The way neutrinos couple to matter in the supernova environment is flavor dependent. This is because the typical energies of neutrinos there, $\sim 10\,\mathrm{MeV}$, are low enough that only ν_e and $\bar{\nu}_e$ can initiate both neutral current and charged current reactions, while ν_μ, ν_τ and their antiparticles experience only neutral current interactions. This has important implications for nuclear physics in this environment. For example, the neutron-to-proton ratio, crucial for some nucleosynthesis processes, can be set by the competition between $\nu_e + n \rightleftharpoons p + e^-$ and $\bar{\nu}_e + p \rightleftharpoons n + e^+$ on the one hand, and hydrodynamic outflow rates on the other, in a process essentially similar to Big Bang Nucleosynthesis (BBN).

Moreover, the energy spectra and/or fluxes of the various neutrino species may differ at various epochs in the supernova or neutron star merger event. This implies that any process that changes neutrino flavor or interconverts neutrinos and antineutrinos can show up in either the supernova neutrino burst signal, the nuclear physics of the environment or nucleosynthesis, or all of these.

In fact, large-scale numerical modeling of coherent neutrino propagation has shown that collective neutrino flavor oscillations can occur in the supernova environment [345], despite the small measured neutrino mass-squared differences and the very large matter densities expected there. The reason for this is that the neutrino fluxes in this environment are so large that the neutrino medium itself becomes important and engenders fierce nonlinearity. Essentially, the weak interaction potentials which govern how neutrino flavor changes depend on the flavor states of the the neutrinos! The collective oscillations that ensue can leave unmistakeable features in a supernova neutrino burst, such as the flavor swaps/splits expected to occur in various supernova epochs. These features can be very dependent on the neutrino mass hierarchy.

Recent calculations have pointed out the importance of neutrino scattering-induced decoherence in supernovae. We now have the quantum kinetic equations that govern neutrino flavor and type evolution in general conditions [346–350]. These suggest that the anisotropic environment of supernovae and neutron star mergers could lead to neutrino-antineutrino interconversion. Interestingly, these processes depend on absolute neutrino masses, and Majorana phases, complementing the potential probes of these issues afforded by neutrinoless double beta decay.

Nucleosynthesis SNe are thought to play a major role in nucleosynthesis. As a source of neutron-rich matter, they have long been a leading candidate for the site of the r-process, the rapid-neutron-capture process responsible for the synthesis of about half of the heavy elements above Fe. One of the candidate SN r-process mechanisms that has been intensely studied takes place in the neutrino-driven wind that blows off the surface of the proto-neutron star [351]. As this high-entropy nucleon gas expands and cools, protons and neutrons freeze out into alpha particles, leaving an excess of free neutrons. Some of αs react, combining to form medium mass nuclei, which then become the seeds for subsequent neutron capture. Despite a great deal of effort, it has proven difficult to make this mechanism work in detail: for plausible conditions, various processes combine to yield a neutron/seed ratio well below that required to synthesize the transuranic elements.

Yet observations of metal-poor halo stars show that r-process synthesis occurred very early in galactic history, with a frequency of about 1/100y, highly suggestive of a SN-associated process. One process that appears to work at very low metallicity uses neutrons produced by neutrino reactions in the pure He zones of the star: as the neutrons capture efficiently on the few seed nuclei present in the He, only a relatively modest neutron source is needed [352]. Such a mechanism could account for the observations at low metallicity, even if some other mechanism operating at later times produced the bulk of galactic metals. A leading candidate for that second mechanism would be r-process synthesis in neutron-rich material ejected from neutron star mergers [353].

SN neutrinos also directly synthesize new nuclei, through a variety of spallation reactions driven primarily by neutral current neutrino scattering. Examples are ^{11}B produce in the C zone and ^{19}F produced in the Ne zone. The "neutrino process" can account for the galactic abundances of these nuclei [354].

Experimental Program The feasibility of detecting SN neutrinos was established with SN1987A. On February 23, 1987, a neutrino burst from a SN in the Large Magellanic Cloud was observed in the proton-decay detectors Kamiokande and IMB [355, 356]. The optical counterpart reached an apparent magnitude of about 3, and could be observed easily in the night sky with the naked eye. Approximately 20 events were seen in the two detectors, spread over approximately 10 seconds, from a SN that occurred 160,000 light years from Earth.

Modern detectors with improved thresholds and volumes in the 10 kton to one Mton range, observing neutrinos from a SN within the galaxy (rather than in the LMC), would be expected to record between $10^3 - 10^5$ events. There is an extensive literature on detector responses and on strategies for extracting oscillation constraints from future data – the basic requirement is an array of detectors capable of mapping out the neutrino "light curve" in ν_es, $\bar{\nu}_e$s, and heavy-flavor neutrinos. A recent summary that contains references to earlier work is [357].

Because the SN neutrino burst is intense and concentrated in time, the neutrino light curve can be followed out to $\sim$ 20s with virtually no background, provided the detector is at modest depth ($\sim$ 2 km.w.e.). This makes SN neutrino detection compatible with other large-detector physics, such as long-baseline neutrino oscillations and proton decay, which also require only moderate depth. SN neutrino detection becomes a secondary use of such detectors – if one is fortunate to have a burst. The frequency of galactic SNe is expected to be $\sim$ 3/100y.

A possible outcome of current large-detector planning is a water Cherenkov detector in the megaton range (Hyper-Kamiokande [358]), the far detector for an upgraded J-PARC neutrino program, and a large liquid argon TPC detector (LArTPC, 34 kT) that would be constructed for the US long-baseline program LBNF [359].

Water detectors have exceptional sensitivity to $\bar{\nu}_e$s due to the charged-current (C) reaction $\bar{\nu}_e$ + p $\rightarrow$ n + e$^+$. Hyper-Kamiokande would record $\sim 2 \times 10^5$ events from a SN located at the center of the Milky Way, while the currently operating detector Super-Kamiokande [360] would record about 10^4 events. The relativistic positron is detected through the Cherenkov cone it produces. The cross section is relatively hard, allowing one to reconstruct the neutrino spectrum and its evolution in time from the positron spectrum. Further sensitivity can be gained by doping the detector with the neutron poison Gd, yielding about 8 MeV of energy per neutron capture. The cross section is nearly isotropic. This is important because flavor oscillations in combination with a fairly hard neutrino spectrum can lead to a backward peaked contribution from electrons and positrons produced by CC scattering off oxygen in water detectors. The resulting angular distortion is a potential signature for oscillations.

The distinctive feature of an argon TPC detector (LArTPC, 34 kT) for SN neutrino studies is its sensitivity to the ν_e component of the SN-ν flux through the CC reaction $^{40}\mathrm{Ar}(\nu_e, e^-)^{40}\mathrm{K}$. Thus Hyper-Kamiokande and LArTPC would be highly complementary. The combined information from ν_e and $\bar{\nu}_e$ detection can indeed provide fundamental additional hints both about the SN explosion mechanism and the neutrino intrinsic properties. The LBNF detector would record about 5×10^3 events from a SN at the galaxy's center. The large CC cross section derives from ^{40}Ar having four unpaired neutrons. The cross section is rather well understood: the Fermi contribution is largely model independent, while much of the Gamow-Teller response has been measured in β decay studies of ^{40}Ti, the isospin mirror of ^{40}Ar [361].

Neutrino elastic scattering (ES) off electrons provides information on the location of the SN, as the cross section is sharply peaked in the forward direction. As both water and LAr detectors track electrons, the ES signal can be extracted by exploiting the directionality of the events. The ν_e and $\bar{\nu}_e$ ES cross sections include NC and CC contributions, while heavy-flavor neutrinos (ν_x) scatter via the NC only. The cross sections are known to high precision. The $\nu_e/\bar{\nu}_e$ ES cross sections are about six times those of the ν_x, but this is compensated in part by the higher flux and energy of ν_x. Thus, with large-volume water and LAr detectors, an accurate decomposition of the SN flux into its ν_e, $\bar{\nu}_e$, and ν_x components should be possible.

Low-energy neutrino astrophysics, including associated nuclear physics of target responses, as well as supernova modeling have traditionally been supported within the US nuclear physics program. For this reason nuclear participation in the SN programs associated with coming large detectors should be supported. Encouraging interdisciplinary involving in detectors like LArTPC could be of benefit to the broader LBNF program: as the nuclear response to $\sim$ GeV LBNF neutrinos is highly nontrivial, other aspects of the program would benefit from additional nuclear physics participation.

Theory: Neutrino Physics and the Explosion Mechanism The solar neutrino program yielded a major discovery, massive neutrinos and flavor oscillations, in large part because of a sustained 30-year theoretical effort to develop a standard model of the Sun capable of predicting the core temperature to an accuracy of better than 1%. The SN neutrino problem is similar in that the impact of a precise determination of the SN neutrino light-curve will be quite limited if we lack a standard model of core collapse. Such a model would also define the thermodynamic path of the r-process, helping guide the laboratory nuclear astrophysics program at FRIB and elsewhere.

The goal of a high-fidelity 3-dimensional model of the explosion mechanism with realistic spectral neutrino transport and nuclear microphysics appears realistic, on a 10-year horizon, given the current rapid advance of computing power. Several groups are now evolving 3D models, though with certain simplifications and without the capability to carry

the calculation out to long times [362, 363]. Because of the importance of the modeling to both neutrino physics and laboratory nuclear astrophysics, more nuclear physics investment in this field is needed.

The nonlinear neutrino background problem has added another layer of complexity to the modeling. It is important to realistically incorporate this physics into the modeling, to determine the effect of flavor physics in the central core on neutrino signals that might be detected on earth.

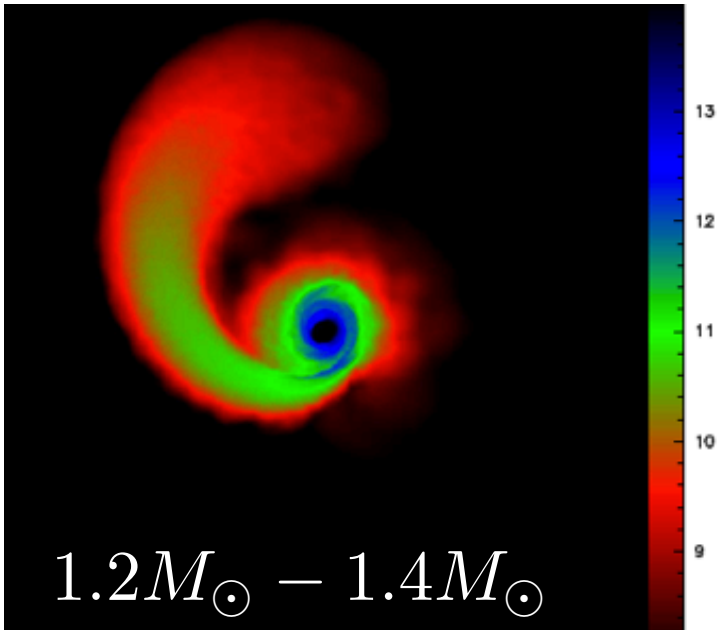

FIG. 22: Simulation of an asymmetric merger of neutron stars, showing an extended tidal tail, a possible site for the r-process. Courtesy of Korobkoin et al.

C. Neutron Stars and their Mergers

Neutrons stars (NSs) are unique laboratories for testing the properties of nuclear matter at extremes of density and isospin [364]. Nearly 2000 NSs have been observed, the vast majority as pulsars. Relatively precise mass determinations are available for about three dozen NSs. Although most deduced masses cluster around a central value of $\sim 1.4 - 1.5 M_\odot$, two recent measurements have established masses near $2M_\odot$, severely constrained models of the nuclear equation-of-state (EoS). Pulsar observations also can provide information on spin rates, ages, and magnetic field strengths. Properties such as radii and surface temperatures can be deduced from optical and x-ray observations of cooling neutron stars, from x-ray bursts on neutron star surfaces, from quasi-periodic oscillations from accreting neutron stars, and potentially from spin-orbit coupling in extremely compact NS binaries. One proto-neutron star has been seen in neutrinos (SN1987A). The detection of the gravitational waves from a merging binary NS system should be possible with Advanced LIGO (begin operations in 2015) and Advanced Virgo (2016), as these instruments reach their design goals. While the rate of such mergers is highly uncertain – estimates range from 0.4 to 40 detections per year – any observations that are made will provide important new information on quadrupole moments and other EoS details.

Maximum Mass A very accurate NS mass was recently determined for PSR J1614+2230 from the Shapiro time delay, $1.97 \pm 0.05 M_\odot$ [365]. From optical data and theoretical properties of the companion white dwarf, a mass of $2.01 \pm 0.04 M_\odot$ was obtained for PSR J0548+0432. Large but less certain masses have been obtained from two "black widow" pulsars with very low mass companions, $2.4 \pm 0.3 M_\odot$ [366] and $2.55 \pm 0.50 M_\odot$ [367]. A conservative interpretation of these data is that the maximum mass of a NS is $\geq 1.93 M_\odot$. This places an important and new constraint on the high-density EoS, eliminating about half of the EoS models in use prior to 2011, as they are not sufficiently stiff at high density to support a $1.93 M_\odot$ NS. The new results tend to disfavor EoSs where exotic phases – deconfined quarks, kaon condensates, hyperons – significantly increase the number of degrees of freedom at high density.

Additional constraints come from estimates of neutron star radii. The available data indicate a radius near 11.5 km for NS with the canonical mass of 1.4 $M_\odot$ [364].

Connections to Laboratory Nuclear Physics This bound on the maximum mass and radius estimates can be translated into constraints on parameters that are conventionally use to describe the nuclear symmetry energy. The allowable values appear to be in good agreement with conclusions derived from laboratory data, including nuclear binding energies, the neutron skin thickness of Sn isotopes, the EoS's derived from flows in heavy ion collisions, the centroids of giant resonances, the dipole polarizability of Pb, and the positions of isobaric analog states [364].

Theory The constraints placed by recent results on NS masses and radii are very significant. If the still larger masses of $\sim 2.4 - 2.55 M_\odot$ obtained for the black widow pulsars are confirmed, the constraints would become very restrictive.

With the advent of Advanced LIGO and Advanced Virgo, the participation of nuclear theorists in this field will grow substantially. The quantitative modeling of NS mergers to connect details of the gravitational wave form with both the merger dynamics and the nuclear EoS will become a high priority. This challenge is very similar to that of core collapse, and in fact involves much of the same physics and many of the same people. Furthermore, a consensus may be emerging that NS mergers are the site where most r-process synthesis takes place. A small amount of neutron rich matter is ejected in the merger, under conditions where neutron capture onto nuclei is quite efficient. Any quantitative understanding of the r-process in such a site will require detailed modeling of the thermodynamics of the ejecta. The ejection of radioactive r-process elements in NS mergers also has observational consequences, producing kilonovae, distinctive optical/infrared transients similar to, but dimmer and briefer than, ordinary SNe [368–370].

D. Nuclear Physics of Dark Matter

Many astrophysical observations – galactic velocity curves, acoustic oscillations implanted on the microwave background radiation, the pattern of large scale structure, discrepancies between distributions of visible matter and gravitating matter in the bullet cluster – combine to show that over 85% of the matter in our universe is dark and unidentified. This dark matter (DM) must be long-lived or stable, cold or warm (slow enough to seed structure formation), gravitationally active, but without strong couplings to ordinary matter. The success of Big Bang Nucleosynthesis (BBN) shows us that the dark matter cannot be baryons. There is no shortage of candidates for the DM: (1) new weakly interacting massive particles (WIMPs); (2) a variant of (1), asymmetric dark matter, motivated by the nearly 20 percent contribution of baryonic rest mass to the total non-relativistic component of the critical density; (3) axions, motivated by proposed solutions of the strong CP problem; (4) electroweak singlets (sterile neutrinos), motivated by the existence of nonzero neutrino mass; (5) primordial black holes, especially with masses around a moon mass; and many, many others. Observations show that we live in a "flat," critically closed universe. This is a space-time symmetry, agnostic to the source of energy density, and DM, that supply the critical energy density. Indeed, we already know that there are several, physically distinct, contributions to closure, e.g., baryon rest mass (about 4 percent), dark energy (about 73 percent), and active neutrino rest mass (probably < 1 percent).

Significantly, nuclear physics plays an important role in the physics and possibly the detection of DM sources (1) through (5). In the US the experimental program in DM detection is supported by High Energy Physics. However, because some nontrivial nuclear physics issues arise, our field's support of the program is important to its success. In particular, "direct detection" experiments to search for WIMP DM (with WIMP masses $\gtrsim$ few GeV) are based on detecting nuclear recoils following the elastic scattering of cosmological WIMPs. While such experiments have been typically analyzed in terms simple couplings to nuclear charge/mass or spin, recent effective theory treatments show that six independent nuclear response functions exist [371]. Several of these responses are connected to nuclear currents that have been shown to greatly enhance the sensitivity of experiments to velocity-dependent interactions.

In addition, the analysis of direct detection experiments, including comparisons among experiments, depend on nuclear matrix elements. Their evaluation requires a combination of nuclear structure calculations [372, 373] and ancillary nuclear physics measurements. In addition, important nucleon-level amplitudes needed in the experimental analysis have been calculated by nuclear theorists, using lattice QCD.

There is also great interest in possible indirect signals for DM from astrophysical sites, arising from DM particle annihilations or decays into a standard-model particles, such as electrons and positrons, protons and antiprotons, photons, and neutrinos [374]. It then becomes important to demonstrate that the candidate signal does not have a more pedestrian origin. That task requires a very thorough examination of possible backgrounds, including issues such galactic cosmic ray propagation, pulsar and other sources of particle acceleration, and conventional gamma ray production mechanisms, including atomic and nuclear physics modeling Important to understanding fluxes and line shapes.

E. Cosmology, the Early Universe, Neutrinos and Nuclear Physics

Cosmology has entered a precision era. Observations with a new generation of ground-based and space-based instruments, in bands from radio to gamma rays as well as high energy neutrino and cosmic ray detectors, may allow the early universe to become a laboratory for probing neutrino physics and other beyond standard model physics in ways complementary to terrestrial experiments. Tritium beta decay endpoint experiments, like KATRIN, targeting neutrino mass associated with electron neutrino flavor, and double beta decay experiments focussed on ascertaining the nature of neutrinos, i.e., whether they are Majorana or Dirac particles, are particularly important because neutrino properties play such an important role in cosmology. Nuclear physics is in many cases the connection between fundamental neutrino physics and the observations.

Arguably precision cosmology began with quantitative efforts to understand the pattern of the light elements. BBN combined a model of the expanding early universe, weak interactions and nuclear cross sections, and primordial abundances inferred from observations to constrain critical cosmological parameters, particularly the baryon-to-photon ratio η and the lepton numbers. The ratio of the amplitudes of the acoustic peaks in the cosmic microwave background (CMB) anisotropies has given us a completely independent measure of η which is in excellent agreement with the BBN value derived from the primordial deuterium abundance. This is a tremendous validation of the BBN enterprise as a probe of early universe physics, and of the experimental nuclear physics program that determined the neutron lifetime and reaction cross sections with the requisite precision [375, 376].

The BBN "tool" will only get even more precise. For example, the next generation of thirty meter-class optical ground-based telescopes may give us the primordial deuterium abundance to better than 2 percent [377], right to the nuclear cross sections uncertainty limits, and the CMB will give us sub-one percent precision on η. Moreover, CMB polarization observations can give us high precision measurements of the relativistic energy content of the universe at the photon decoupling epoch (i.e., $N_{\rm eff}$), and an independent and reasonably precise measurement of the primordial helium abundance, breaking the current degeneracy of these two. When combined with large scale structure observations, especially of the Lyman alpha forest hydrogen clouds at high redshift, CMB observations also give a measure of the "sum of the light neutrino masses '' Σm_ν, " which is a measure of the convolution of the neutrino mass with the relic neutrino energy spectra, effectively measuring the free streaming length of neutrinos in the early universe. Combining this information with light element abundance and BBN provides a powerful means for constraining new neutrino and other BSM physics.

We currently do not know : (1) the neutrino mass hierarchy, (2) the absolute masses of neutrinos, and (3) the CP-violating phase in the unitary transformation between the neutrino energy/mass states and the weak interaction/flavor states. We also do not know if there are additional mostly "sterile" neutrino states, and we are ignorant of what the mass scales and vacuum flavor mixing properties of these might be, though the cosmological and BBN tools discussed above allow us to eliminate large swaths of sterile neutrino mass/mixing parameter space, and future observations and experiments will open up even better avenues for constraint.

Weak gravitational lensing of the CMB and large scale structure observations promise increasingly tight constraints on Σm_ν, possibly to the point of revealing the neutrino mass hierarchy or a degeneracy in mass. This is a tremendous opportunity, and a key motivation for neutrino-less double beta decay experiments. Current estimates are that these experiments can yield a signal only if nature has chosen the inverted neutrino mass hierarchy, or that there are degenerate neutrino masses. Finding such a signal would have profound implications for cosmology. Either the cosmological observations find a signal for Σm_ν consistent with the inverted hierarchy, or they see nothing. The latter result might well imply that underlying assumptions inherent in the cosmological analyses are incorrect, *e.g.,* perhaps the relic neutrino energy spectra have non-Fermi-Dirac black body shapes, pointing to new BSM physics operating in the early universe. Another possibility is that the cosmological observations point to the normal mass hierarchy. A positive signal in double beta decay would then point to either new physics at higher energy scale, or call into question our understanding of how smaller large scale structure forms. Either way, there will be a fascinating synergy between the lab and the observations.

XII. THEORY

Achieving progress in nuclear theory is essential for realizing the scientific opportunities with fundamental symmetries, neutrinos, neutrons and related areas of nuclear astrophysics. Theory interprets the results of experimental measurements in terms of the fundamental questions being addressed by the subfield. Theory generates new ideas for answering those questions, thereby motivating new experimental directions. Theory develops the tools needed to translate these ideas into quantifiable predictions. And theory delineates the broader implications of fundamental symmetry tests and neutrino studies, connecting them with complementary studies at the high energy and cosmic frontiers.

For each of the four broad experimental thrusts outlined in Table I, nuclear theory has made substantial progress since the 2007 NSAC Long Range Plan. Some of this progress has been highlighted in other subsections. Here, we briefly summarize some of these achievements:

Neutrinoless $\beta\beta$-decay: The generator-coordinate method has brought density-functional theory to the problem of nuclear matrix elements, clarifying the effects of shape and pairing. QRPA calculations have also incorporated density functionals and can now include essentially complete single-particle spaces. Shell-model calculations have become more powerful, with effective interactions improved and the effects of truncations starting to be addressed through an effective decay operator. These three approaches are now being systematically compared and the sources of differences better understood. The problem of suppressed two-neutrino matrix elements is being investigated, with two-body currents from chiral EFT considered as one of the sources. The use of measured occupation numbers has reduced theoretical uncertainty in some isotopes.

Overall, although the uncertainty remains substantial, research that promises to reduce it is fully underway. Experimental progress has brought more nuclear structure theorists into the area than ever before and the continued improvement of existing calculations together with the introduction of new methods will lead to significant progress in the next few years.

Electric Dipole Moments: The development of state-of-the-art methods for computing the cosmic baryon asymmetry have refined the confrontation of EDM search results with the matter-antimatter asymmetry. The development of an effective field theory framework for parity and time-reversal violating hadronic and few-body interactions and its application to a variety of EDMs have sharpened the interpretation of EDM results in terms of possible BSM sources of CP-violation. New scenarios have been invented for generating the matter-antimatter asymmetry at the electroweak scale that provide new benchmark sensitivities for future EDM searches and complementary tests of CP symmetry in heavy flavor systems. Pioneering computations of hadronic matrix elements of the quark electric and chromo-electric dipole moments as well as four-quark CP-violating operators have been completed using Dyson-Schwinger equations and lattice QCD.

Lepton Properties and Interactions: Dispersive computations of the γZ box graph contributions to parity-violating electron-proton scattering have revealed previously unknown contributions to the parity-violating asymmetries and motivated future, low-energy measurements. Analyses of higher-twist and charge symmetry-violating contributions to parity-violating deep inelastic electron scattering have sharpened the interpretation of the corresponding asymmetries. New scenarios involving "dark" Z bosons and analyses of $Z'\gamma$ mixing have provided new examples of the unique BSM sensitivity of parity-violating Møller and deep inelastic scattering. Three-loop computations of the muon anomalous magnetic moment have identified previously-omitted contributions associated with the pion polarizability, quantified their potential impact, and provided new motivation for future polarizability measurements. Analyses of charged lepton flavor violation have motivated the development of a possible search for electron to tau conversion at an electron-ion collider. An analysis of the model-discriminating power of measurements of mu-to-e conversion on different target nuclei, with realistic uncertainty estimates has been carried out.

Radioactive Decays and Other Tests: Studies of the relative sensitivity of β-decay and LHC searches for possible new scalar and tensor contact interactions have identified the complementary reach of low- and high-energy searches. New analyses of supersymmetric electroweak radiative corrections have identified benchmarks for future tests of CKM unitarity and lepton universality in light of direct searches for supersymmetric particles. New lattice QCD results have provided first principles computations of scalar and tensor charges as needed to reliably interpret β-decay searches for scalar and tensor interactions. Recent theoretical work has delineated the complementarity of EDMs and experiments with polarized neutron/nuclei to possible new time-reversal violating interactions, while others have identified the sensitivity of torsion-balance experiments to "dark" forces. A first principles computation of the parity-violating pion-nucleon coupling has been achieved using lattice QCD. Radioactive decays and other tests: The most precise calculation of the helicity-suppressed ratio $R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ within the Standard Model, based on two-loop chiral perturbation theory has been completed.

Achieving this progress has required drawing on a diverse range of theoretical expertise, including BSM model building and phenomenology, non-equilibrium and finite-temperature quantum field theory, electroweak radiative corrections, effective field theory, non-perturbative QCD, nuclear many-body theory, and computational nuclear physics. A similar statement applies to study of astrophysical processes, such as the chains of reactions responsible for solar energy generation and the dynamics of supernovae. Looking to the next decade, there exist a number of important challenges and opportunities, motivated in part by the prospected experimental advances and by expected progress in related areas of high energy physics and cosmology:

- *Hadronic and nuclear matrix elements*: Obtaining robust computations of nuclear matrix elements for $0\nu\beta\beta$-decay and the nuclear Schiff moment and first principles computations of hadronic matrix elements for electric dipole moments and semileptonic weak interactions; providing more reliable computations of the hadronic contributions to the muon anomalous magnetic moment; computing time-reversal odd asymmetries in low-energy neutron-nucleus scattering; evaluating the low-energy constants for the strangeness-conserving hadronic weak interaction using lattice QCD;

- *Implications for the energy frontier*: Carrying out a comprehensive phenomenology for disentangling the $0\nu\beta\beta$-decay mechanism; continuing to delineate the implications of LHC BSM searches for precision measurements of parity violating asymmetries in electron scattering, tests of CKM unitarity and lepton universality using β-decay and pion leptonic decays, and β-decay decay correlations; continuing to delineate sensitivity of low-energy searches for new ultralight degrees of freedom, such as "dark bosons";

- *Implications for the origin of matter*: Obtaining more precise quantum transport computations of the cosmic baryon asymmetry for weak scale baryogenesis and leptogenesis scenarios, including resummations of space-time varying background fields; exploration of low-scale leptogenesis scenarios and their relationship to $0\nu\beta\beta$-decay studies; evaluation of the baryon asymmetry in novel weak scale scenarios and evaluating the implications of EDM searches;

- *Implications for matter in the early universe and astrophysical processes*: Evaluating of nuclear response functions for dark matter direct detection experiments; probing the physics of neutrino rest mass in the early universe; further development of high-fidelity 3D supernova simulations, particular carrying out such calculations to late times; and determining the effects of neutrino oscillations on the neutrino signal from a supernova;

- *Implications for Standard Model weak interactions*: Carrying out *ab initio* computations of few-body parity-violating asymmetries and evaluating the sensitivity to leading order low-energy constants for the strangeness-conserving hadronic weak interaction (HWI); and providing more reliable predictions for neutrino-nucleus scattering cross sections as needed for the interpretation of neutrino oscillation experiments;

The opportunities for significant advances in experimental sensitivity described throughout the remainder of this White Paper underscore the need for commensurate progress on these theoretical challenges. While an exhaustive discussion of each challenge goes beyond the scope of this document, we highlight a few in order to illustrate the need for significant advances and the theoretical program that could be implement to achieve them:

- *Nuclear matrix elements*: It is widely appreciated that the matrix elements for the light Majorana neutrino-exchange mechanism in $0\nu\beta\beta$-decay are presently subject to factors of three or more uncertainty, translating into an order of magnitude uncertainty for the rate. While this uncertainty does not diminish the significance of a potential observation of the neutrinoless decay, it does impact the design of the next generation, tonne-scale efforts hoping to for a sensitivity to effective masses of order 10 meV. Should the matrix elements be smaller than conventionally accepted, the scale of detectors and the level of background rejection would need to be increased. Recent suggestions of a more significant quenching of the axial vector coupling could further exacerbate this uncertainty. The situation regarding matrix elements for TeV-scale lepton number violating mechanisms for the decay is considerably less advanced than for the light Majorana neutrino case. Clearly, a concerted effort to address this challenge for nuclear many-body physics is called for.

  The prospects for reducing the uncertainty in the light-Majorana-neutrino exchange matrix element are good. Several nonperturbative methods, now under development, will translate ab initio calculations that combine interactions from chiral EFT with a powerful many-body approach such as coupled cluster theory into effective shell model interactions and operators that can be applied near mid-shell. More powerful supercomputing will allow larger shell-model spaces to take advantage of the new operators. New correlations will be added to the promising generator-coordinate method. Ab initio methods and EFT currents will allow the quenching of g_A, which must be due either to complex correlations or many-body currents, to be fully understood in lighter nuclei and clarified significantly in the heavier nuclei that undergo $\beta\beta$ decay. The predictions of models for

other observables will be studied carefully; the correlations between those observables and the neutrinoless $\beta\beta$ matrix element should allow uncertainty to be better quantified.

The short-range matrix elements that govern the exchange of heavy exotic particles will be studied with the same methods, though here, because research is less advanced, it is more difficult to estimate the degree of progress the next few years will produce.

Similar challenges pertain to the nuclear Schiff moment that could be responsible for the EDMs of diamagnetic atoms, such as ^{199}Hg and ^{225}Ra. The current uncertainty for ^{199}Hg is particularly large, and even the sign of the sensitivity to the isovector time reversal-violating and parity-violating (TVPV) pion-nucleon coupling is open to question. As discussed in Section VII, this uncertainty significantly clouds the interpretation of the most stringent EDM limit achieved to date in terms of new, fundamental sources of CP-violation, some of which may be responsible for the cosmic baryon asymmetry. Although an initial set of ideas for refining the many-body computations have been outlined in a recent ACFI-FRIB workshop[5], the number of theorists devoting significant effort to this problem is less than a handful.

- *Hadronic matrix elements*: As discussed in Section VII, underlying sources of CP-violation that could be responsible for generating the matter-antimatter asymmetry may first appear through the EDMs of strongly interacting systems, such as the neutron. A prime example is the quark chromo-EDM (CEDM) that characterizes the CP-violating interaction of gluons and quarks. As outlined in Ref. [76], the sensitivity of the neutron EDM to the CEDM is not known to better than one order of magnitude, despite heroic efforts by a variety of theorists. Even in the simpler system of the ρ-meson, which is not of experimental interest but provides a useful theoretical testing ground, the results of Dyson-Schwinger equation and QCD sum rules computations differ by an order of magnitude. With prospects for a factor of 100 improvement in the sensitivity of the neutron EDM with the U.S. nEDM experiment, reducing this level of theoretical uncertainty to well below an order of magnitude stands as an important goal. Similar statements apply to other sources of CP-violation that could generate the EDMs of nucleons or the TVPV pion-nucleon couplings that govern the nuclear Schiff moment.

  As the result of a recent ACFI workshop[6], a concerted effort by nuclear theorists to address this challenge is being developed, drawing on a variety of first principles approaches. With sufficient workforce investment, a comprehensive set of Dyson-Schwinger equation results with state-of-the art kernels could be obtained in the next five years. Lattice QCD computations with uncertainties commensurate with the present spread of QCD sum rules, quark model, and Dyson-Schwinger computations could be achieved on a similar time scale. A roadmap for progress will appear in a separate document.

- *The origin of baryonic matter*: Computing the baryon asymmetry from the sources of CP-violation that may appear in EDMs is a challenging problem for non-equilibrium, finite-temperature field theory. While the transport problem for the interpretation of heavy ion collisions draws on similar methods, the challenge for baryogenesis has received less attention in the nuclear physics community. At its heart, the problem requires characterizing the evolution of states in the presence of space-time varying masses during the electroweak symmetry-breaking transition in the early universe. Recent progress has been made when the BSM CP-violation involves new spin-0 particles, where a solution that resume the space-time varying masses in a well-defined expansion scheme has been demonstrated. The corresponding challenge for fermionic sources is considerably more daunting, given the interplay with spin degrees of freedom. Solving this problem would help reduce the present theoretical uncertainty in baryogenesis computations to well below an order of magnitude. Similarly challenging open theoretical problems pertain to the dynamics of electroweak symmetry-breaking, whose understanding will allow one to determine whether or not the conditions for baryogenesis existed during this era. A particularly thorny issue is gauge-invariance: while recent work has allowed one to obtain gauge-invariant computations of the baryon washout factor, gauge-invariant perturbative computations of the tunneling rate for the transition remain to be obtained.

- *The interpretation of precision tests*: Translating the results of precision measurements of parity-violating asymmetries and weak decay observables into robust implications for new interactions in the early universe requires progress on two fronts. From the SM side, one must have adequate control over strong interaction and many-body dynamics, so that any difference between a SM prediction and experimental result is a *bona fide* signature of BSM interactions. On the BSM side, one must quantify the implications of searches for new particles at the

[5] See http://www.physics.umass.edu/acfi/seminars-and-workshops/fundamental-symmetry-tests-with-rare-isotopes
[6] http://www.physics.umass.edu/acfi/seminars-and-workshops/hadronic-matrix-elements-for-probes-of-cp-violation

energy frontier into benchmark sensitivities for precision nuclear physics observables. Recent progress on the former, including the identification and computation of the $Z\gamma$ box graph effects and scalar and tensor form factor computations, have been noted above. One challenge that remains is to reduce the uncertainty in the $W\gamma$ box graph that enters the extraction of $V_{\rm ud}$ from neutron and nuclear β-decay, while another is to obtain more reliable computations of the hadronic light-by-light contribution to the muon anomalous magnetic moment. The challenge for obtaining benchmark sensitivities in light of LHC results includes the subtleties in the interpretation of the latter given the hadronic environment. For a given BSM scenario such as supersymmetry (SUSY), the LHC may be unable to discover the SUSY particles if they are light but live in a "compressed" spectrum region and/or have electroweak production rates. Identifying how low-energy precision measurements may provide a window into these regions and identifying the necessary sensitivity remains an on-going challenge, particularly in light of the evolving situation with LHC results.

- *Astrophysics and cosmology*: A particularly important focus for the next decade will be on supernovae, aiming for a more robust interpretation of SN signals in terms of underlying fundamental interactions. Further development of high-fidelity 3D supernova simulations, particularly carrying out such calculations to late times, will facilitate making contact with the electromagnetic and nucleosynthetic signals from such explosions. Such work will help define the thermodynamic paths of possible supernova r-processes. It will also be important to determining the effects of neutrino oscillations on the neutrino signal from a supernova, including the unique aspects of the flavor physics that arise because of the high density of trapped neutrinos.

  A more recent opportunity for the field is to explore the role of nuclear physics in the interpretation of limits from direct detection dark matter searches. Dark matter particle interactions with nuclei can generate a variety of nuclear responses. There is an important role for nuclear theory in describing those response functions and in relating them to more familiar electroweak responses.

  There also exist important challenges for nuclear theory related to the physics of neutrino rest mass in the early universe, especially as it relates to weak decoupling, the relic neutrino density, light element synthesis (e.g., deuterium, ^{4}He, and ^{7}Be/^{7}Li), constraints on the sum of the light neutrino masses and cosmological determinations of the neutrino mass hierarchy, and BSM physics in the neutrino and other sectors. Key theoretical issues include understanding neutrino propagation and scattering in the ultra-high entropy nuclear matter/quark-gluon plasma in the QCD epoch, and neutrino flavor quantum kinetics during the weak decoupling/freeze-out and BBN epochs. The latter calculations can sharpen up the relation between small net lepton numbers, light element yields, $\mathrm{N_{eff}}$, and the relic neutrino energy spectrum.

1. Resources & Workforce

Achieving an adequate theoretical workforce constitutes the primary resource needed to address these and other challenges and to realize the opportunities for significant advances. This workforce consists of a "core" group of theorists whose primary research emphasis is fundamental symmetries and neutrinos. It is strengthened through the engagement of other nuclear theorists who devote some fraction of their effort to particular problems that overlap with their expertise, such as computations of the nuclear Schiff moment in heavy nuclei as needed for the interpretation of diamagnetic atom EDMs. In addition, the core theorists have successfully involved theorists from related fields, such as high energy theory, in aspects of fundamental symmetries and neutrinos questions that bear on their interests. This situation is illustrated in Figure 23.

While the synergy between the theoretical core and other areas of theoretical expertise have been a strength, the overall scope of the core effort remains relatively small compared to other subfields of nuclear science. Compared to the total DOE fundamental symmetries and neutrinos research budget (inclusive of both theory and experiment), the theoretical component comprises just 7% of the total. It also comprises less the 10% of the total DOE nuclear theory budget. The number of DOE-funded theoretical post-doctoral researchers is again less than 7% of the total number of post-doctoral FTE's for fundamental symmetries and neutrinos research.

While one should take these numbers somewhat impressionistically, they nevertheless reflect the mis-match between the growing experimental effort and the theoretical workforce. Importantly, much of the progress achieved in the last decade has resulted from Ph.D. student and post-doctoral research. With the absence of a sufficiently robust post-doctoral employment opportunities, Ph.D. students face challenges in remaining within nuclear theory while devoting their research to fundamental symmetries and neutrinos. The absence of new faculty positions targeting fundamental symmetries and neutrinos creates a similar conundrum for post-docs. For both students and post-docs, career advancement the requires moving to a different area of research, either within or outside of nuclear theory.

The advances in fundamental symmetries and neutrinos theory despite these funding and workforce challenges has been enabled, in part, by the success of senior members of the core workforce in obtaining non-agency funding

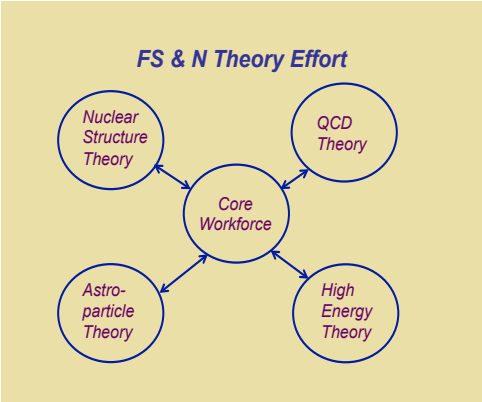

FIG. 23: Theory for fundamental symmetries & neutrinos in nuclear physics is carried out by a core workforce that interfaces with theoretical efforts in other areas of nuclear physics, such as nuclear structure theory and QCD. There exists significant interaction with high energy theory, cosmology, and astroparticle theory as well.

through combinations of laboratory LDRD awards and start-up funds associated with moves to new positions. Clearly, this situation is not sustainable for the long-term. Clearly, a growth in the workforce at all levels and enhanced agency research support is essential for realizing the theoretical opportunities discussed throughout this document and maximizing the impact of the experimental investments. These needs could be addressed by one or more of the following mechanisms:

- Enhanced individual P.I. research support for students and post-docs
- Bridge funding for new theoretical faculty positions
- Funding of a theoretical Topical Collaboration targeted to this subfield
- Establishment of a topical center for fundamental interactions (see Sec. XII 2)
- Support for a nuclear theory-wide initiative in computational physics, as described by other White Papers

2. *Theory-Experiment Interface: A Topical Center for Fundamental Interactions*

In contrast to the other major nuclear physics research thrusts, for which Jefferson Lab, Brookhaven, and FRIB provide or will provide a geographic focal point for the respective communities, fundamental symmetries and neutrinos does not rely on a single major facility as its "home". This situation creates particular challenges for theory, which relies on a geographically dispersed core and synergistic interactions with theorists in related areas. It also means that there exists no natural meeting ground for theorists and experimentalists, much as there exists at other national laboratories.

The community recognizes the need for, and supports the creation of, a topical center that would address this need, functioning much as a national laboratory theory group would do were a single major facility to exist for this subfield. The activities of the center would include:

- In-house theoretical research related to the experimental program, with opportunities for post-doctoral mentoring and Ph.D. student training
- Hosting and support for targeted, topical workshops that address key problems in the field and related areas and that enable the development of new research directions and collaborations
- Hosting of theoretical collaboration meetings as well as opportunities for theory-experiment interaction, including an annual meeting of the Fundamental Symmetries topical group & Neutrinos (*https://www.phy.ornl.gov/mailman/listinfo/nufunsym-l*)

- A visiting researcher program that provides opportunities for junior and senior theorists to develop a new research direction that is then carried on back at the researchers' home institutions
- Joint post-doc and Ph.D. student arrangements with researchers at other institutions
- Maintenance of a "living website" that provides a compendium of latest results in both theory and experiment, much as the LEP electroweak working group and the LHC ATLAS and CMS public wiki's provide.

The establishment of such a center would presumably be made after a national competitive process. At present, a prototype is being developed at the University of Massachusetts Amherst, whose activities encompass many of those identified above. In its first 1.5 years of operation, the Amherst Center for Fundamental Interactions (ACFI) has hosted seven targeted, topical workshops and one experimental review; initiated a visiting researcher program; and launched a website for the Beyond the Standard Model in Nuclear Physics Working Group that is developing the compendium of theoretical and experimental results in a manner to be a resource for the community. A more complete view of the ACFI scope of activities, including workshops, can be found at *http://www.physics.umass.edu/acfi/* . The ACFI is presently funded out of University funds. Based on experience to date, it is estimated that operating such a national centers at level requisite for addressing community needs would be roughly $300K/year (indirect cost included). The ultimate location of a topical center would result from an open, nationally competitive process.

XIII. FACILITIES AND INFRASTRUCTURE

Unlike other nuclear physics subfields, there is no central, unifying user facility for the fundamental symmetries, neutrinos, neutrons, and related nuclear astrophysics community (hereafter referred to as FS&N community). Instead, as summarized below, our community employs a broad range of different facilities with unique infrastructure needs.

A. Underground Labs

The Sanford Underground Research Facility (SURF) in South Dakota is a deep (4850 feet, 4300 mwe) underground research facility with future expansion possibilities. At present, the Davis Campus at SURF houses the LUX dark matter experiment, the Majorana Demonstrator neutrinoless double beta-decay experiment, and two low-background counting facilities which provide important support to the experimental program. The Ross Campus at SURF will soon undergo significant expansion in order to house the CASPAR accelerator and another low-background counting facility. There are near-term (several years time scale) mid-scale expansion possibilities at SURF, including the possible renovation of space of sufficient size to host a 200-kg-scale ^{76}Ge-based double beta decay experiment. Although it will be possible to expand the facilities at SURF such that the laboratory could host a large scale experiment, the timescale for such an expansion will be CY 2019 or later, due to the major excavation requirements for such a space and the subsequent need for the installation of a waste rock handling system.

At the SNOLAB facility (6800 feet, 6010 mwe) in Canada, our community continues to play an important role in many experiments sited there, including the SNO+ experiment, the HALO supernova neutrino experiment, and also a broad range of dark matter experiments. A relevant and timely point here is that SNOLAB has not yet made a commitment to any particular experiment for a currently-unoccupied cavity (the "Cryopit") sufficiently large to house a tonne-scale experiment. A selection process for this space is currently underway.

Currently the EXO-200 experiment is performed at the Waste Isolation Pilot Plant (WIPP) in New Mexico. However, it is not sufficiently deep for next generation NDBD experiments.

Also US groups participate in the KamLAND-Zen at Kamioka in Japan and the CUORE experiment at LNGS in Italy.

The future US effort in NDBD will require a network of radioassay facilities, including low-background gamma-ray counting systems, such as the Berkeley Low-Background Facility, and dedicated inductively coupled plasma mass spectrometry systems.

B. Neutrinos

A highly-enriched, compact-core reactor would constitute an ideal neutrino source for a very short baseline neutrino oscillation experiment. Three suitable candidate sites in the US have been identified: the NIST research reactor,

the HFIR reactor at Oak Ridge National Laboratory (ORNL), and the Advanced Test Reactor at Idaho National Laboratory. The merit of these reactors stems from the combination of their ~ 1 m compact cores, thus permitting the shortest possible baselines, with their use of highly-enriched fuel, which provides for a simpler spectrum.

Neutrinos of high energy ($\sim$ GeV) are produced at NuMI and the Booster Neutrino Beam at Fermilab. Members of the NP community are deeply involved in the MINERvA and MiniBooNE experiments (and others) using these beams. A new long-baseline beam at Fermilab is planned for LBNF; this experiment will also draw on NP expertise for understanding of neutrino interactions. A uniquely high-quality source of neutrinos in the few tens of MeV regime from pion decay at rest is available at the Spallation Neutron Source at Oak Ridge National Laboratory; NP community members plan to use this source for low-energy neutrino scattering (COHERENT) and oscillation (OscSNS) experiments.

C. Muons

A major development since the previous Long Range Plan has been the construction of a muon campus facility at Fermilab for the $g-2$ and Mu2e experiments. Although the construction of this new facility was funded by High Energy Physics, our community has and will continue to provide significant contributions to these flagship experiments. The development of this campus was the result of a coordinated effort designed to simultaneously meet the needs of both of these experiments, and included, for example, upgrades to the Booster and the conversion of the Tevatron's former anti-proton target into a muon source for the $g-2$ experiment.

D. Electrons

The parity-violating electron scattering program at the Jefferson Laboratory in the 12 GeV era will feature the MOLLER and PVDIS experiments. Achieving these experiments' physics goals will require multiple infrastructure upgrades, including increased cryogenic capacity (for the scattering targets), upgrades to the infrastructure for the measurement of the electron beam polarization, and upgrades on the accelerator-side for control of helicity-correlated parameters and on the experimental-side for measurements of helicity-correlated parameters.

E. Neutrons

At the Spallation Neutron Source (SNS), the physics program on the Fundamental Neutron Physics Beamline is underway, and the beamline's cold neutron flux is consistent with the initial physics design. The SNS also provides for the world's most intense pulsed source of neutrinos, and several such neutrino physics experiments have been proposed for the SNS. In the longer term, the prospect of a Second Target Station at the SNS would present not only the opportunity for a significant increase in the cold neutron flux available to a neutron experiment, such as a neutron EDM experiment, but also the potential to increase the sensitivity of the OscSNS neutrino oscillation experiment.

At NIST, a new high-flux beamline currently delivers the highest integrated cold flux available in the US, and a further increase following an upgrade to the cold source is anticipated in the coming years.

Finally, the performance of the ultracold neutron (UCN) source at the Los Alamos National Laboratory (LANL) ranks among the best worldwide and is also, at present, the only operating UCN source in North America. The upgrade of the LANL UCN source is currently under way. An increase of approximately a factor of 10 in produced UCN density is expected.

XIV. APPLICATIONS OF FUNDAMENTAL SYMMETRY AND NEUTRINO TECHNOLOGIES TO SOCIETAL ISSUES

The application of nuclear physics both to societal issues and to other fields of science began at the turn of the 20th century. As our understanding of the nucleus and its properties advanced, the sophistication of the applications increased. Today, our field contributes significantly to nuclear medicine, the world's source of energy, and to nuclear non-proliferation and nuclear security. Over the past $5-10$ years the FS&N subfield has made significant contributions to applied nuclear physics. These range from improved medical imaging, to atom trap trace analysis for climate modeling, to the characterization of nuclear material damage under extreme radiation conditions. Here we provide a few specific examples of applications of recent FS&N technologies.

1. The prototype detector for Majorana allowed the 1st measurement of reaction in-flight (RIF) neutrons at the National Ignition Facility (NIF). RIF neutrons are fusion products from super-thermal fuel ions. They are the highest energy particles produced in a burning plasma and represent only 10^{-4} of the total neutron production in nuclear fusion. RIFs provide key diagnostics of the plasma properties, probing the temperature, the density, and the stopping power. The difficulty in measuring these tertiary reaction products is the huge background from the much higher yield of primary and secondary reactions in the burn. This problem was overcome in 2013 at NIF using a variation of the prototype detector design from Majorana (see Fig. 24.)

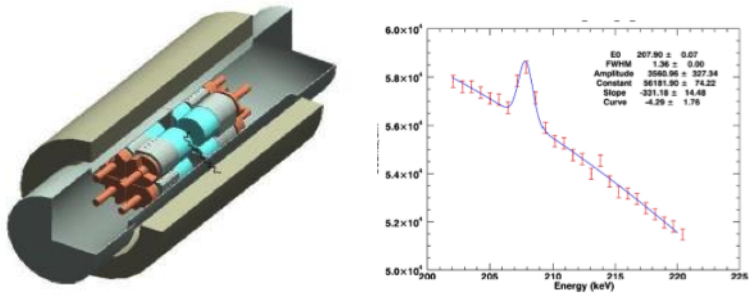

FIG. 24: Reaction-in-Flight neutrons, with energies above 15 MeV, were measured for the first time in any laboratory plasma using a variation of the prototype detector for Majorana. The measured signals showed that the cold dense fuel surrounding the hotspot in a NIF ignition capsule is a strongly coupled, electron degenerate plasma.

2. Ultra Cold Neutrons allow unique fission studies of surface sputtering and fission-induced damage in nuclear material. Fission fragments deposit about 200 MeV of energy within $\sim 20\ \mu$m on a psec timescale. This results in a collective bulk material response, causing surface material ejection and extreme damage that is a concern for both nuclear reactors and stockpile stewardship. The very short range of ultra cold neutrons and the ability to vary their penetration into nuclear materials make them ideal probes of surface fission damage and sputtering processes (see Fig. 25).

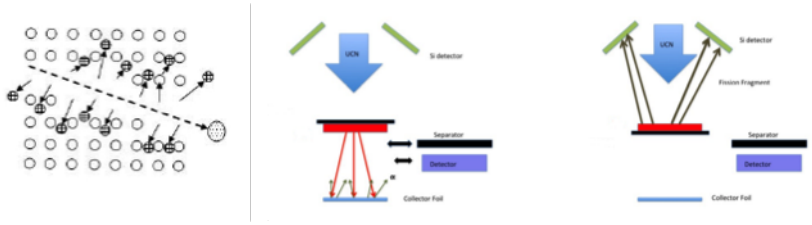

FIG. 25: Ultra Cold Neutrons allow unique fission studies of surface sputtering and fission-induced damage in nuclear material.

3. Atom Trap Trace Analysis (ATTA), using the same techniques as in nuclear EDMs searches, are addressing problems in earth and climate science. Following the flow and circulation of the Earth's oceans and groundwater is central to climate modeling. Measurements of trace noble gases are used for assessing groundwater availability, studying atmospheric histories from ice cores, and understanding oceanic circulation. Many of these applications are made possible by ATTA, which requires extremely small samples compared to more conventional techniques to make Ar and Kr isotope concentration measurements to 1 part in 10^{16}(see Fig. 26).

4. Antineutrino spectra from reactor neutrino experiments are testing and constraining the nuclear databases. Deviations of the antineutrino spectra measured in the near detectors at reactor neutrino experiments from expectations are placing strong constraints on the nuclear databases used for reactor and stockpile stewardship studies. The measurements have pointed to discrepancies in fission fragment yields between the US and European databases that have important implications for reactor decay heat (see Fig. 27).

5. Geo-neutrino measurements constrain the Earth's radiogenic heat source. The Earth's internal heat drives several important dynamic processes, such as plate-tectonic motion, earthquakes, and volcanic eruptions. The total heat loss from the Earth (47 ± 3 TW), is a balance between cooling of the mantle, energy loss from the core, and

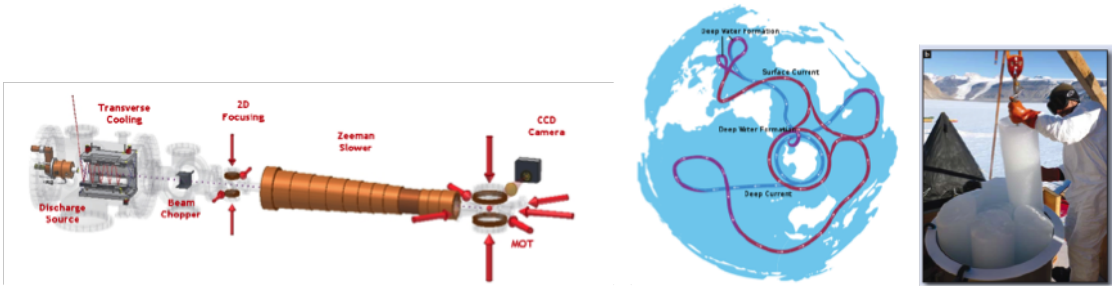

FIG. 26: Atom Trap Trace Analysis (ATTA), using the same techniques as in nuclear EDMs searches, are addressing key problems in earth and climate science.

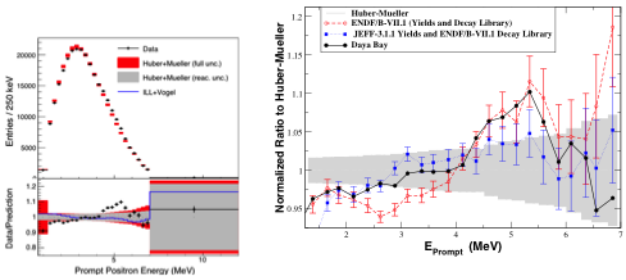

FIG. 27: The antineutrino spectra measured in the near detectors at reactor neutrino experiments are placing strong constraints on the nuclear databases used for reactor and stockpile stewardship studies.

radiogenic heat production. Experimental data from Borexino and KamLAND showed that anti-electron neutrinos emanating from the earth, so-called geoneutrinos, determine the Earth's radiogenic heat source from ^{238}U and ^{232}Th. Assuming that uranium and thorium are spread uniformly in the mantle, the KamLAND findings suggest that about 11 of the 47 TW come from the radioactive decay of those elements. A similar calculation for Borexino yields about 18 TW. (see Fig. 28).

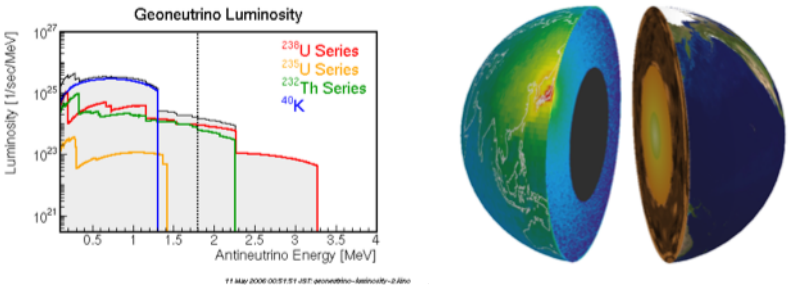

FIG. 28: Geo-neutrino measurements are constraining the Earth's heat source.

6. Development of Liquid Xe Detectors for Medical Imaging Positron Emission Tomography (PET) PET provides 3-D imaging of tumors by injecting ^{18}F into the patient and measuring the back-to-back 511 keV annihilation photons. Liquid Xe (LXe) detectors, that are the bases of many dark matter and double beta-decay searches, are now being tested by several groups around the world to improved on both energy and position resolution of the positrons emitted in PET scanning. Researchers are aiming to achieve an energy resolution of about 4% and a spatial resolution of a few mm. This would represent about a factor of three improvement over current commercial detectors, significantly improving medical imaging technology (see Fig. 29).

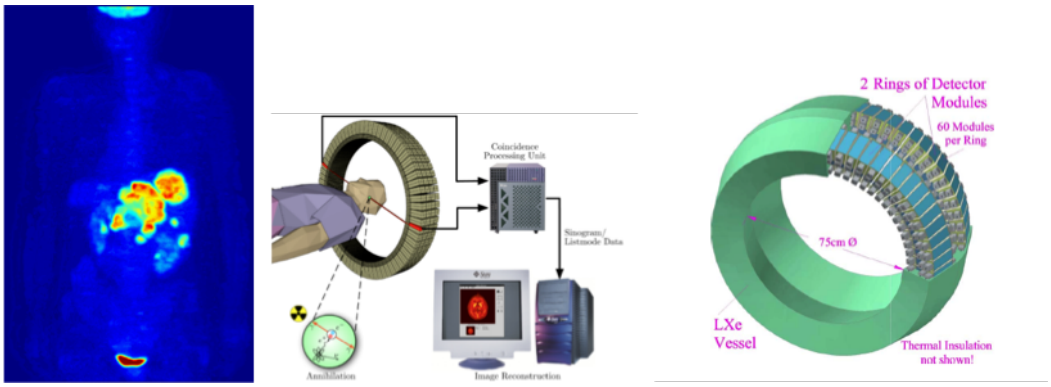

FIG. 29: A prototype LXe detector for PET scanning could improve this medical diagnostic technique by a factor of three.

XV. INTERFACES WITH NUCLEAR ASTROPHYSICS

There are two main interfaces of Nuclear Astrophysics with the FS&N subfield: One is in the area of neutrino astronomy and the other is in various aspects of the origin of heavy elements in our universe through the rapid neutron capture process (r-process). A number of other interface questions are associated with the role of neutrino interactions during the quark hadron phase transition of the Big Bang and the roles of weak interactions, ranging from triggering the type II supernova collapse to driving the neutronization of matter in the curst of neutron stars. These events are all associated with the emission of intense neutrino flux.

The solution of the solar neutrino problem in the last decades was one of the greatest breakthroughs in physics. It provided an explanation for the longstanding discrepancy between the observed and predicted solar neutrino flux by the experimental confirmation of neutrino oscillations. This effort led to the new field of neutrino astronomy, for probing directly the interior of our sun and providing information on supernova explosions. The analysis of the pp-chain neutrino spectrum provides direct information that confirms the physical conditions of the solar interior predicted by the standard solar models. The detection of neutrinos from the CNO cycle in future experiments will offer a unique opportunity to independently determine the metalicity of the solar core. This requires detailed and much better knowledge of the strength of CNO reactions at solar temperatures. A precise measurement of these reactions and a reliable interpretation of their contributions to the solar neutrino spectrum can only be done in cosmogenic radiation free underground environments. This requires the development of a next generation high intensity underground accelerator facility that enables the measurements of very low cross sections for the most critical nuclear reactions.

The development of an underground accelerator facility was one of the top three recommendations of the Nuclear Astrophysics town meeting.

The origin of the heavy elements in the universe is one of the eleven most challenging open questions for all of physics in the 21st century, and it is a principal motivation for the construction of new radioactive ion beam facilities world-wide, and FRIB in particular. Access to the most neutron-rich nuclei is one of the main initiatives of the nuclear structure community and the recommendation with the highest priority of the joint nuclear structure and nuclear astrophysics town meeting in Texas A&M. The leading scientific goal of FRIB is to access the most neutron-rich nuclei and their associated nuclear properties. Nuclear properties such as masses of the most neutron-rich nuclei and their associated weak interactions via the measurements of beta-decay rates, beta-delayed neutron emission probabilities, and the role of neutrino interactions remain the most important aspects of understanding the r-process. The specific roles of other processes such as the Light Element Production Process (LEPP) process, assumed to occur in the very first star generations and how they impact the observed solar-abundance distributions are important for the determination of a more robust r-process signature. This is an essential step for interpreting reliably the r-process abundance distribution that presently guides the FRIB experimental program.

The timely completion of the FRIB facility and its instrumentation was the top recommendation of the Nuclear Astrophysics town meeting.

XVI. INTERNATIONAL PERSPECTIVES

It is impossible to give a complete survey of all international efforts in this area, and the discussion below is restricted to a few areas.

The European physics community sees a rich and broad program in FS&N. Europe provides substantial support for HEP and NP programs, but the European efforts in specific areas that are funded in the US by the DOE NP FS&N program tend to be fragmented between different agencies and different countries. For instance, certain areas of the European FS&N program come under CERN, some under NuPPEC, some under ApPEC, and some under other agencies. A community-wide, organized US FS&N program should give the US an advantage in positioning her scientists in this field. A major question for the US program is how will the quid pro quo contributions to non-US projects that are implied in a true internationalization in this area be organized, and how will the inter-agency and inter-divisional within agency priorities be balanced.

The CERN treaty mandates CERN Council to plan and coordinate particle physics throughout the member states (even for those projects not at CERN). This is formally done through the CERN strategy process, which about every five years engages in extensive review with the community to formulate an overall strategy. The recent CERN strategy document assigned as first priority the completion of the LHC program, and European particle physicists were pleased to see the US HEP's P5 recommendations agree with that priority. Amongst the three other highest priority areas, the CERN strategy recommended that "Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan." This is explicit acknowledgement that all particle physics experiments projects cannot be done in Europe, and that we must cooperate to utilize the strengths of all regions. Note that in Europe CERN Council contains direct participation from the funding agencies, so the CERN Strategy is a statement of what is expected to be funded, not just what would be nice.

Another body which coordinates FS&N physics in Europe is ApPEC, the Astroparticle Physics European Consortium. ApPEC will soon publish an updated roadmap, which will endorse European participation in LBNE and Hyper Kamiokande. These experiments will open up many opportunities for FS&N physics other than long-baseline neutrino oscillations, such as proton decay, indirect dark-matter searches and both burst and relic supernova neutrinos. ApPEC also endorses a strong program of studies in single-beta and double-beta decay to probe neutrino mass. On double-beta decay the draft road map emphasizes that reaching the target sensitivity for next-generation experiments will require international cooperation, and says : "The agencies urged the underground laboratory directors to prepare the ground for an international evaluation in $2-3$ years time leading to a selection of the most promising technologies for the next generation detectors worldwide." The US should make sure it is playing a full part in that selection and that all relevant parties are fully consulted.

Another topic of common interest in this area of physics is the measurement of particle electric dipole moments. The scientific case for such measurements remains strong, however experimental progress has been difficult given the technical complexity of the measurements. Europe has seen a consolidation in the number of planned experiments, with the three major efforts now reduced to two. The current room-temperature experiment at PSI will be run and upgraded, and a new room-temperature effort is planned at the ILL. Meanwhile R&D will continue on a cryogenic experiment, with the long-term goal of a fully cryogenic experiment combining both groups in $12-20$ years.

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