Nuclear Science and the New Standard Model:
Fundamental Symmetries and Neutrinos in The Next Decade

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I. EXECUTIVE SUMMARY

This White Paper summarizes the recent accomplishments and major opportunities for the study of neutrinos and fundamental symmetries in nuclear physics. Community input for this White Paper was obtained at two "Pre-Town Meetings" held in Santa Fe (November, 2006) and Pasadena (December 2006) as well as a DNP-sponsored Town Meeting held in Chicago (January 2007). Through this process, the community has addressed historic opportunities for nuclear science in developing the "new Standard Model" of fundamental interactions. Indeed, the recent remarkable results in neutrinos and fundamental symmetries have provided us with unique opportunities that were only imagined at the time of the last long range plan. These opportunities bear on three of the eleven questions identified by NSAC as characterizing the mission of 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 ?

In addressing these questions, the community has identified two experimental efforts with major discovery potential that could have broad impact both within and beyond nuclear physics: the search for neutrinoless double β-decay and searches for the permanent electric dipole moments of the neutron, neutral atoms, and nuclei. The discovery of either neutrinoless double β-decay or a non-zero electric dipole moment would have important implications for our understanding of the origin of baryonic matter as well as for the nature of the "new" Standard Model. Either discovery would change the way we think about the cosmos at the most fundamental level, much as the discoveries of parity-violation in nuclear β-decay, of neutrino oscillations, and of a new state of matter in heavy ion collisions have altered our paradigms.

The community has also identified a targeted program of precise nuclear physics studies of neutrino properties and Standard Model electroweak observables that will complement information that may be obtained from the next generation of high energy colliders. These studies will help us determine the absolute masses of the neutrino, the hierarchy of neutrino masses and pattern of flavor mixing, and detailed characteristics of presently unseen forces, such as supersymmetry, that may have played a more visible role at earlier times in the history of the cosmos. They will also help us map out the internal landscape of the proton, explain the violent explosions of stars, and characterize the weak interactions of nuclei that governed the generation of heavy elements.

The study of neutrinos and fundamental symmetries in nuclear science stands at a historic juncture for two reasons. First, the past five years have been a period of enormous advances, including the discovery of neutrino oscillations, the solution of the solar neutrino problem, and the development of experimental and theoretical techniques that have opened the way for low-energy probes of the New Standard Model with unprecedented power. The experimental results in neutrino oscillations and precision measurements are among the most highly-cited in nuclear physics and have generated high levels of enthusiasm for our field among young scientists. Second, the physics community as a whole is entering a period of great discovery, with the imminent operation of the Large Hadron Collider, the advent of ton-scale searches for cold dark matter, and new probes of the mysterious dark energy responsible for cosmic acceleration. The next decade is one in which we are likely to witness a revolution in our understanding of the way the universe works. The recent advances in neutrinos and fundamental symmetries in nuclear physics have made it possible for nuclear science to be a full partner with high energy physics, cosmology, and astrophysics in this exciting era.

Fully realizing our historic opportunities will require investing in a major new nuclear physics Initiative in neutrinos and fundamental symmetries. The success of this initiative depends critically on the construction of Deep Underground Science and Engineering Laboratory that will provide a domestic home base where searches for neutrinoless double β-decay and precise studies of the low energy solar neutrino spectrum can be carried out. At the same time, this initiative will require continuing and new investments in studies of fundamental symmetries and neutrinos at other major nuclear physics facilities and robust support for university-based research groups. Therefore:

- **We strongly recommend investment in a "New Standard Model Initiative", anchored by the construction of a Deep Underground Science and Engineering Laboratory, and including experimental searches for neutrinoless double beta-decay and permanent electric dipole moments together with a targeted program of precision measurements of Standard Model processes and neutrino properties.**

In order to provide a road map in carrying out this Initiative, the community has developed a set of priorities:

1. We recommend construction of a Deep Underground Science and Engineering Laboratory, and its complement of experiments in neutrinoless double beta decay, solar neutrinos, and nucleosynthesis. In the shorter term, we recommend immediate support for modest scale experiments in neutrinoless double beta decay, antineutrino oscillations at nuclear reactors, and measurements of the absolute neutrino mass in nuclear beta decay.

2. We strongly recommend capital investment in, and support for, the nEDM experiment at the FNPB. We also recommend support for searches for rare-isotope EDMs and R&D toward a storage-ring based deuteron EDM measurement.
3. We strongly recommend a targeted program of precision electroweak studies at facilities such as FNPB, JLab, LANSCE, NIST, and BNL. Present and future opportunities having unique sensitivities to new physics include measurements of the muon anomaly, neutron decay parameters, and polarized electron scattering asymmetries.
4. We recommend a unified experimental and theoretical program in nuclear physics to construct a standard supernova neutrino model to understand how elements are produced in these explosions, and to develop a secure foundation from which to investigate other cataclysmic astrophysical events, such as gamma-ray bursts.
5. We recommend support for nuclear physicists involved in interdisciplinary efforts such as measurements of the neutrino mixing angle θ_{13} through reactor and long-baseline experiments, direct and indirect searches for dark matter and sensitive tests of charged lepton flavor violation.
6. We strongly recommend new investments in the next generation of nuclear theorists who are critical to the future of neutrino and fundamental symmetry studies, and targeted support for initiatives to solve the key scientific problems identified in this White Paper.

The best time to begin the program we outline here is *now*, while we can capitalize on the experience gained in making the historic measurements of the recent past

II. INTRODUCTION

The mission of nuclear science is to explain, at the most fundamental level, the origin, evolution, and structure of the baryonic matter of the universe. Although the baryons comprise only a small fraction of the total cosmic energy density (about 5 %), they are the most relevant component to human life. The objective of nuclear science is to explain what caused the universe to develop this net excess of baryonic matter; how it evolved as the universe expanded and cooled to form the hadrons and nuclei that we observe today; and how the dynamics of nuclei and their interactions with other hadrons and leptons govern other processes in todays universe, such as the production of energy in the sun and the explosion of supernovae. Our mission is complementary to those of particle physics, atomic physics, cosmology, and condensed matter physics, but clearly has important areas of intersection with all of these fields.

The study of neutrinos and of fundamental symmetries in nuclear physics is a key component of our mission and one that has a long history in the field. The observation of parity-violation in the β-decay of polarized ^{60}Co together with the observation of parity-violation in the decay of polarized muons provided smoking gun evidence for the presence of parity violation in the weak interaction as proposed by Lee and Yang. This nuclear physics discovery provided a cornerstone for the Standard Model of particle physics that stands as one of the triumphs of 20th century physics. It also provided fundamental insights into the radioactive decay of nuclei that govern the abundance of elements in the present universe.

In the fifty years since the discovery of parity violation, nuclear physicists have made several key discoveries that have both uncovered the nature of the basic forces of nature and illuminated the properties and interactions of baryonic matter. At the time when nuclear β-decay studies began providing key insights into the nature of the weak interaction, nuclear physicists also began the quest to understand the synthesis of the elements and generation of energy in stars. Ray Davis and collaborators built the first solar neutrino experiment with the goal of demonstrating the existence of nuclear fusion reactions in the solar interior. This pioneering effort led to the field of neutrino astrophysics and was recognized through the 2002 Nobel prize in physics.

From the first reports in 1968 the Davis experiment, and then subsequent measurements, indicated a deficit of solar neutrinos. This deficit was recently resolved by the evidence for flavor transformation in solar neutrinos produced by the SNO experiment and the demonstration of the oscillation phenomenon by the KamLAND experiment. These are results of historic importance in physics and establish a new paradigm that dramatically changes central themes in nuclear physics. Indeed, the observation of neutrino oscillations has both revolutionized our understanding of neutrinos and provided the first indications of physics beyond the Standard Model as written down by Glashow, Weinberg, and Salam. As with the discovery of parity violation in nuclear β-decay, nuclear physicists played a central role in the discovery of neutrino oscillations and in the elucidation of their implications.

Today, the field is on the verge of a new era of discovery and insight. New searches for the permanent electric dipole moments of the neutron, neutral atoms, nuclei and charged leptons could uncover the violation of CP-symmetry needed to explain the excess of visible matter over antimatter in the present universe. Similarly, searches for the neutrinoless double β-decay of nuclei could demonstrate that neutrinos are Majorana particles and, together with determinations of the neutrino mixing angle θ_{13}, demonstrate the viability of scenarios in which decays of heavy neutrinos in the early universe produced the matter-antimatter asymmetry. The potential for these discoveries is unmatched by the reach of present and future high energy colliders and represents a unique opportunity for nuclear physics to have broad impact during the coming decade.

At the same time, precise nuclear physics studies of neutrino properties and of unsuppressed Standard Model processes will provide key insights into the nature of the larger framework in which the Standard Model is embedded. For example, although we know that neutrinos are massive particles, we do not know the absolute scale of neutrino mass or the hierarchy of neutrino mass eigenstates. Precise measurements of ^{3}H β-decay and of reactor neutrino oscillation properties are essential in addressing these fundamental questions. Similarly, new and more precise measurements of observables that are not suppressed in the Standard Model could reveal tiny deviations from Standard Model expectations that would indicate the presence of additional interactions between quarks and leptons that were more important at earlier periods of cosmic history. Such observables include the anomalous magnetic moment of the muon, parity-violating asymmetries in the scattering of polarized electrons from protons and electrons, and the weak decays of neutrons, nuclei, pions, and muons. Precise measurements of these observables complement what we may learn from high energy searches for new particles at the Large Hadron Collider, and recent advances in experimental precision, together with theoretical interpretability, make these studies powerful tools in the search for the "new Standard Model".

In addition to having broad impact, the study of neutrinos and fundamental symmetries in nuclear physics has important synergies with other aspects of our field, such as the effort to understand the origin of heavy elements or the quark substructure of the nucleon. Indeed, the synthesis of heavy elements in supernova explosions is strongly influenced by the presence of neutrinos. In fact 99 % of the emitted energy is in neutrinos, and the flavor composition of these neutrinos directly affects the neutron-proton ratio in the material available for r-process nucleosynthesis. The flavor composition of the neutrinos arises from their masses and mixing angles and is a key ingredient for explosive nucleosynthesis.

In the same vein, measurements of parity-violating electron scattering asymmetries, parity-violating interactions between nucleons, and neutrino-nucleus scattering cross sections are shedding new light on poorly understood aspects of the strong interaction. In the past decade, for example, a dedicated program of parity-violating electron scattering measurements have yielded the most precise bounds on contributions from strange quarks to the nucleon's electromagnetic structure. Future measurements using parity-violation and neutrinos will help in taking us beyond the quark model picture of the nucleon that has been the standard model of hadron structure for several decades and revealing novel aspects of sea quarks and quark-quark and quark-gluon correlations in ways that complement other studies at the Jefferson Laboratory and RHIC.

In short, the potential for fundamental discoveries and insights that are broadly recognized through the study of neutrinos and fundamental symmetries in nuclear physics is unprecedented. The level of recognition outside our field (*e.g.*, through citations of experimental results) is unmatched in nuclear science and the level of interest and enthusiasm among young scientists extremely high. In what follows, we summarize the recent accomplishments that have led us to this unique position and outline a future program of investments aimed at realizing the historic opportunities. Fully doing so would require a major new initiative in neutrinos and fundamental symmetries in nuclear science. In what follows, we hope to convince our colleagues of the value of such an investment.

III. RECENT ACCOMPLISHMENTS: HIGHLIGHTS

The high potential for discovery and insight with studies of neutrinos and fundamental symmetries in nuclear physics builds on an outstanding record of accomplishments since the completion of the 2002 Long Range Plan. Here we highlight some of these accomplishments:

- Solution of solar neutrino problem, discovery of flavor mixing of electron neutrinos with SNO, beginning of precision phase of solar neutrino astrophysics. The heavy-water experiment SNO was able to measure both the charged-current and neutral-current interactions of solar neutrinos, and found that only 1/3 of the active neutrinos from ^{8}B decay in the sun arrived at earth as electron neutrinos, clear evidence that new neutrino physics was responsible for the solar neutrino problem [16–19].

- Oscillations of reactor antineutrinos observed with KamLAND [22, 23]. At the site of the former Kamiokande experiment a new scintillation detector was able to see the energy-dependent disappearance of reactor antineutrinos over a baseline of 185 km. The results confirmed the solar neutrino observations of flavor conversion and pinpointed the Large Mixing Angle as the correct oscillation solution. The KamLAND result has received over 1000 citations.

- The world's most precise measurement of the anomalous magnetic moment of the muon that could provide the first low-energy signature of virtual supersymmetric particles and that is one of the most highly cited results in our field (over 1000 citations).

- The most precise determination of the weak mixing angle off the Z^0 resonance using parity violating Moller scattering, providing the most stringent test to date of the running of this essential Standard Model parameter.

- Definitive determinations of the strange quark contributions to the nucleons electromagnetic form factors using parity-violating electron-proton and electron-nucleus scattering and confirmation of theoretical predictions of hadronic effects in electroweak radiative corrections.

- A test of quark-lepton universality to better than ±0.05 % via CKM unitarity and the comparison of high precision studies of superallowed nuclear beta decays with muon and kaon decay rates. For their dedicated work on that subject, J. Hardy and I. Towner were awarded the 2006 Bonner prize in Nuclear Physics.

- Direct neutrino mass measurements reach 2-eV sensitivity. The Mainz experiment on the beta decay of tritium successfully reduced systematic and statistical errors to reach a limit on the mass of the "electron neutrino" (a superposition of mass eigenstates) of 2.2 eV [30]. That result, in concert with the mass-squared differences from oscillation data, is sufficient to limit the masses of all the active eigenstates to 2.2 eV.

- Completion of a comprehensive set of calculations of supersymmetric effects in low-energy precision observables, recognized by the 2005 Dissertation Award in Nuclear Physics to A. Kurylov.

- New theoretical breakthroughs in neutrino flavor transformation in supernovae, nucleosynthesis with neutrinos in SN and GRBs, role of weak interactions in SN shock dynamics. The intimate connection between detailed properties of neutrinos and the supernova mechanism has been exploited to set limits on massive neutrinos, to reveal a weakness in nucleosynthesis theory that may point to mixing with a sterile neutrino, and to provide a plausible driver for revival of the shock that ultimately ejects the mantle of the star during the explosion. In particular we are now able to successfully incorporate neutrino-neutrino interaction terms in the neutrino propagation near the supernova core [120].

- High statistics (4,000 neutrino) searches for high-energy gamma-ray sources and astrophysical diffuse flux from the AMANDA detector, and the start of construction for the IceCube neutrino observatory.

- Development of an effective field theory framework for the interpretation of hadronic parity violation in few-body systems that represent the first significant advance in the field in over two decades and that provides a road map for a robust program of few-body parity violation experiments at nuclear physics facilities.

- Advances in theoretical interpretation of neutrinoless double beta decay. Theoretical arguments favor the possibility that neutrinos are their own antiparticles, and will be found to mediate neutrinoless double beta decay. Substantial model-dependence of the nuclear matrix elements has now been understood and markedly reduced in a concerted and broadly based theoretical initiative.

- Substantial technical developments that have opened the way for orders of magnitude improvement in searches for the permanent electric dipole moments of the neutron, electron, neutral atoms, and deuteron, revolutionizing the discovery potential of this quest to uncover CP-violation outside the Standard Model.

Details of these accomplishments, along with description of other important achievements in the field, are described in various sections below. It suffices to say, however, that the modest investment of resources in studies of fundamental symmetries has lead to a demonstrably high impact both within and beyond nuclear physics.

IV. OPPORTUNITIES

As noted in the Introduction, the field of fundamental symmetries and neutrinos is on the verge of a new era of discovery and insight. Two experimental efforts have a particularly high discovery potential: the search for neutrinoless double β-decay ($0\nu\beta\beta$) and searches for the permanent electric dipole moments (EDMs) of the neutron, neutral atoms, and deuteron. The observation of a non-zero rate for $0\nu\beta\beta$ would establish that nature violates total lepton number (L) and open the possibility that L-violating decays of heavy Majorana neutrinos in the early universe led to the generation of the baryon asymmetry. Such a result would also reveal that the appropriate neutrino mass term in the Lagrangian of the new Standard Model is a Majorana mass term. Similarly, the observation of a non-vanishing EDM in the next generation of experiments would be consistent with the level of CP-violation needed for generation of the baryon asymmetry at the electroweak scale, and such a result could provide the first indications of CP-violation beyond that of the Standard Model CKM sector. Either discovery would, thus, have revolutionary impact both within and beyond the field of nuclear physics.

In addition to these opportunities, a targeted program of precise measurements of neutrino properties and unsuppressed Standard Model observables is poised to provide key insights into the nature of the new Standard Model. Below, we describe these opportunities after discussing the two experimental efforts with major discovery potential.

A cornerstone for the nuclear physics role in developing the new Standard Model is the construction of a Deep Underground Science and Engineering Laboratory, together with the suite of low-background experiments – including $0\nu\beta\beta$ and solar neutrino observations – for which it would provide an essential home. As experiments reach unprecedented sensitivity levels in their quest for the new Standard Model, the need for a dedicated underground facility for future experiments is accentuated. For instance, the next-generation $0\nu\beta\beta$ decay experiments target a decay half-life of $\sim 10^{27}$ years, and would require a detector background rate in the signal window to be $\sim$1 count per ton of target material per year. At such stringent background levels, backgrounds of cosmic origin, especially fast neutrons [63], will become a limiting factor to further improvement in the physics reach. The effects of these ineliminable cosmic backgrounds can be lessened by mounting the experiments at greater depths.

The signal rates for events caused by processes at the frontier of physics may be only a handful per year, but at the earth's surface, twenty thousand cosmic-ray muons per minute pass through each square meter. Several techniques exist for mitigating this background, and depth is only one of them. For certain experiments, depth may be the only available strategy; for others it may be one of several options. The graph in Figure 1 shows the rate per nucleus of interactions of cosmic-ray secondary neutrons with energies above 100 MeV as a function of depth. Those neutrons are the most difficult component of the cosmic rays to shield. The adjacent panels show the signal rates for WIMP dark-matter particle interactions, for neutrinoless double beta decay, and for solar neutrinos. For many experiments, there are other strategies to reject backgrounds, and not every cosmic-ray neutron will mimic a signal, but the comparison shows that it is easier to carry out such searches at great depths. Where signals from the new physics will appear is unknown, but the ranges on the scales to the right cover what is expected for three major physics campaigns. As experiments become bigger and more sensitive (moving down on the graph), the need for depth becomes more acute. If the expected signal rate falls below the cosmic neutron background rate, an experiment may still be practical. Among the strategies that can be used are a) shielding, b) energy selection, c) association of an event in time with another event, d) topology of events. Even when those techniques are available, however, depth is still an advantage. Experimenters can dispense with costly shields required for each experiment at shallower depth in favor of the overburden in a shared deep facility. Deep experiments lessen the concern that an observed signal might actually be background. Depths in the range 4000-6000 m.w.e. are sufficient to meet the needs of this kind of physics. There is a depth limit, set by the rate of neutrino interactions, beyond which experiments obtain no further gains. That depth limit is about 10000 m.w.e.

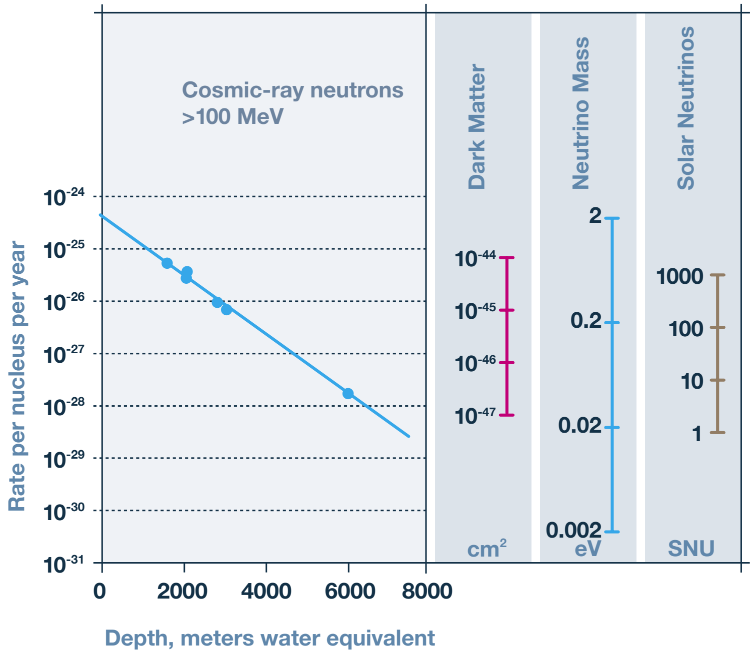

FIG. 1: Left panel: rate per nucleus of events caused by cosmic-ray muons, plotted against the depth underground in meters water equivalent (m.w.e.) [63]. Left center panel: rate per nucleus of dark-matter particle interactions for cross sections from 10^{-44} to 10^{-47} cm^2. Right center panel: rate of neutrinoless double beta decays for effective (Majorana) neutrino masses from 2 to 0.002 eV. Right panel: rate of solar neutrino interactions for typical nuclear cross sections (the "SNU," or solar neutrino unit, is the rate per 10^{36} target atoms.) All rates, both signals and background, are on the same common scale of rate per nucleus. The goal for each of these experiments argues for a laboratory at a depth near 6000 m.w.e. or 2200 meters. This plot is taken from the DUSEL S1 Study [132].

The National Science Foundation (NSF) recognizes the need for a dedicated deep underground research facility, and has initiated the process of developing the Deep Underground Science and Engineering Laboratory (DUSEL). The funding and construction of DUSEL is central to the "New Standard Model" initiative and to the US nuclear physics program in general, as it will be a premier domestic facility where exciting and pressing research in our field and related fields can be conducted. These research topics include:

- developing a complete understanding of neutrino properties, including neutrino mass, mixing parameters, Dirac or Majorana nature of the neutrino, and possible CP violating phases in the neutrino sector which may provide an explanation of the universe's baryon asymmetry;
- understanding the origin of the elements and nucleosynthesis reactions and rates;

- understanding the role of neutrinos in stellar evolution and the creation of heavy elements;
- direct searches for dark matter;
- searches for nucleon decay; and
- geoneutrinos.

There exists strong overlap between high profile research efforts at the core of the nuclear physics mission and DUSEL, including neutrinoless double beta decay searches, solar neutrinos, nuclear astrophysics measurements and supernovae searches. Proposed experiments for DUSEL will involve nuclear physicists working in close cooperation with other disciplines in high-impact research fields. In addition, DUSEL will provide a platform for other disciplines, such as geomicrobiology, earth sciences, engineering and significant education and public outreach.

We now turn to a detailed discussion of the physics opportunities that would be provided by DUSEL and other nuclear physics facilities.

A. Neutrinoless double β-decay

The origin of matter in the universe (i.e. why there appears to be essentially no antimatter), and the origin of mass itself, are among the most fundamental problems in physics. If neutrinoless double beta decay were observed, it would signal that neutrinos and antineutrinos are the same particle, that lepton number is not conserved, and additional mass terms are allowed in the Lagrangian for matter particles. Additional information about CP violation would then be needed to gain some confidence that the matter-antimatter asymmetry could be ascribed to the properties of neutrinos.

Double beta decay is the only practical approach to determine the critical neutrino property, whether they are their own antiparticles or not (For recent reviews, see Refs. [121–123]). While it is widely appreciated that the observation of a non-zero $0\nu\beta\beta$ rate would establish the Majorana character of the neutrino, the absence of a such an observation could also indicate that neutrinos are Dirac particles if future oscillation experiments determine that the mass hierarchy is inverted (see below) or ordinary β-decay finds evidence for a non-vanishing neutrino mass. Even though there exists a long-standing theoretical prejudice in favor of a Majorana mass term because it allows for the see-saw mechanism that could explain the tiny scale of m_ν in a natural way, recent investigations of string theory-based models suggest that Dirac neutrinos occur far more often in such constructions. Moreover, the strength of "naturalness" arguments explaining the small value of m_ν is open to question in light of the failure of such arguments in the case of the cosmological constant. It may, indeed, be the case that m_ν is simply unnaturally small. Thus, the only convincing proof that neutrinos are their own antiparticles and that nature violates total lepton number will be obtained from experiment.

As has been emphasized in several studies, it is important to search for $0\nu\beta\beta$ in a variety of systems at comparable levels of sensitivity, since the presence of a peak in the spectrum for a single isotope where one expects a $0\nu\beta\beta$ signal could also be caused by some previously unknown ordinary radioactivity. The occurrence of such an "accident" in more than one isosope is highly unlikely. Moreover, despite recent theoretical nuclear structure advances, there remains sufficient uncertainty in the computations of nuclear matrix elements that a fortuitous nuclear structure suppression of the rate in a particular isotope may put the observation of a non-zero rate out of experimental reach, even if the effective neutrino mass lies within the range implied by the inverted hierarchy. Thus, searching for $0\nu\beta\beta$ in at least three isotopes is considered a minimal strategy.

In this context the U.S. nuclear physics community has a unique opportunity to make a major discovery by pursuing two $0\nu\beta\beta$ experiments. A recent claim of a statistically significant $0\nu\beta\beta$ signal in ^{76}Ge by the Moscow-Heidelberg collaboration has generated considerable controversy and highlights the need for a second ^{76}Ge experiment with comparable sensitivity. To that end, the Majorana collaboration [51] has requested support for a 60-120 kg enriched array that could confirm or refute the claim of a non-zero rate and serve as the first stage toward the development of a ton-scale experiment that could explore the inverted hierarchy range if no signal is observed in the first state. Similarly, U.S. nuclear physicists are playing a key role in the CUORE experiment [48] that is a European experiment being mounted in Gran Sasso and for which nuclear physics capital support is being sought. Together with the EXO ^{136}Xe double beta decay experiment [45] that is under construction and that is being supported by the DOE office of High Energy Physics, the Majorana and CUORE efforts would provide the minimal triad of isotopes needed for a robust $0\nu\beta\beta$ program. As a result of several review-panel recommendations, DOE has approved CD-0, a statement of mission need, for a generic double-beta-decay program.

These opportunities must be viewed in the context of other international efforts. In the cavity recently occupied by the SNO heavy water detector it is proposed to install a liquid scintillator detector, SNO+, one of the aims of which is a large-mass ^{150}Nd double-beta decay experiment (this isotope is perhaps the most favorable candidate in terms of rate for a given effective neutrino mass). There is US participation in this Canadian experiment. NEMO-III [46, 47] is a European double-beta-decay experiment with some US involvement that is partially funded. The COBRA CdTe double-beta decay experiment [49] is receiving R&D support only from foreign sources. A European ^{76}Ge experiment, GERDA [50], is moving ahead towards a 45-kg enriched isotope array. In Japan, the MOON [52, 53] and CANDLES [54] double beta decay experiments (^{100}Mo and ^{48}Ca respectively) are under construction at the several-kg scale.

The larger experiments will be sensitive to an effective neutrino mass below 100 meV. Most of the degenerate mass range will be explored. Reaching the lifetimes that are predicted for much of the inverted hierarchy and the normal hierarchy, however, will require ton-scale separated-isotope experiments. Thus an objective for currently proposed experiments is a quantitative basis for background estimation for the next round of scaled-up detectors.

While the observation of a non-zero $0\nu\beta\beta$ rate would provide convincing evidence for the Majorana character of the neutrino, one would also like to derive information on the absolute scale of neutrino mass from a measured rate. To that end, input from nuclear theory is essentially, as the rate depends on the product of the effective mass squared and the decay matrix element squared. Since the 2002 Long Range Plan, substantial progress in reducing the theoretical uncertainty in the matrix element has been achieved in the context of the Quasiparticle Random Phase Approximation (QRPA), where calibration of the effective interaction to the observed two-neutrino decay rate reduces the spread of predictions. Nevertheless, considerable challenges remain, as the differences between QRPA and nuclear shell model computations are not yet understood, and recent theoretical work implies a need to scrutinize the impact of short range correlations. In tandem with the experimental opportunities, there exists a corresponding theoretical opportunity to apply state-of-the art nuclear structure techniques to address these issues. Similarly, in order to determine the absolute scale of m_ν one needs to know that potential competing effects from the exchange of other Majorana particles (*e.g.*, supersymmetric particles) are less important than light Majorana neutrino exchange. Application of effective field theory techniques to this problem and studies of lepton flavor violation in other contexts (see below), could further clarify the $0\nu\beta\beta$ mechanism.

B. Electric Dipole Moments, CP-Violation, and the Origin of Matter

It is considered axiomatic that the initial, post-inflationary conditions were matter-antimatter symmetric. If so, then the particle physics of the post-inflationary era would have to be responsible for generating a nonvanishing baryon number density. Forty years ago, Sakharov identified the three key ingredients for any successful accounting for this density: (1) a violation of conservation of baryon number B; (2) a violation of both C and CP symmetries; and (3) a departure from thermal equilibrium at some point during the cosmic evolution.

In principle, these ingredients could have generated the baryon asymmetry at any moment in the post-inflationary epoch up to the era of electroweak symmetry breaking. At one extreme, baryogenesis might have occurred at very early times, associated with particle physics at scales much greater than the electroweak scale, as in the case of leptogenesis discussed above. At the other end is the possibility of electroweak baryogenesis (EWB).

During the coming decade, experiments that probe new weak scale physics will test EWB with revolutionary power. In the most optimistic scenario, these experiments will uncover the building blocks of EWB and point to the new physics scenario that consistently incorporates them. Even null results, however, would be interesting, as they would imply that EWB is highly unlikely and point to higher scale scenarios such as GUT baryogenesis or leptogenesis.

The search for electric dipole moments in electrons, neutrons, and atoms aims to discover new physics in the CP violating sector. Recent measurements carried out at the Institut Laue-Langevin (ILL) in Grenoble, France, have set a limit on the neutron electric dipole (nEDM) limit of $d_n < 3 \times 10^{-26}$ e-cm. Similarly, a group at the University of Washington has obtained a bound on the ^{199}Hg EDM of 2×10^{-28} e-cm, setting new constraints on $\bar{\theta}_{\rm QCD}$ that characterizes the strength of CP violation involving gluons, chromo-EDMs of quarks that characterize CP violating quark-gluon interactions , and CP violation in supersymmetric models. In an effort to continue this success, researchers are working towards development of improved experiments in the neutron, deuteron, and in atoms.

A particular focus in nuclear physics falls on the neutron EDM. As the simplest, long-lived neutral hadron that can possess an EDM, the neutron is an especially attractive candidate for EDM searches. A new effort is underway at the Spallation Neutron Source that aims to improve the sensitivity over past d_n searches by a factor of 100. Achieving this level of sensitivity would place the U.S.-based d_n search ahead of its European competitors at ILL and PSI. From the standpoint of the baryon asymmetry, this measurement will provide a particularly powerful probe. In order to explain the baryon asymmetry in the Minimal Supersymmetric Standard Model (MSSM), for example, the level of CP-violation needed would imply a neutron EDM with magnitude of $\sim 10^{-28}$ e-cm, a level possibly within the reach of the SNS EDM goals. The reach of the neutron EDM is illustrated in Fig. 2, which gives an illustrative representation of the MSSM parameter space needed to achieve the observed baryon asymmetry, present constraints from the electron EDM and new particle searches at LEP, the prospective sensitivity of future d_e and d_n searches, and the reach of the Tevatron and Large Hadron Collider. It is important to note that the reach of the EDM searches exceeds the reach expected for the LHC.

Significant advances are also underway in searching for EDMs of other systems. Researchers have successfully cooled and trapped radioactive species such as ^{225}Ra, ^{226}Ra, and ^{209}Rn in their effort of establishing the feasibility of next generation atomic EDM measurements. New ideas for measuring the deuteron EDM with a storage ring experiment at the Brookhaven National Laboratory are presently being explored. In all cases, these new experiments offer the promise of orders of magnitude improvement in sensitivity.

It is important to note that the EDMs of each of these systems carry a complementary dependence on the CP violating parameters of a given new physics model. For example, the electron EDM is quite insensitive to CP violation in the strong sector, making systems with quarks the only viable probe of strong CP violation. In contrast, the neutron, lepton, and neutral-atom EDMs generally depend differently on the complex phases entering any new EW CP violation. Consequently, it is essential to carry out measurements in a variety of systems in order to provide the most comprehensive probe.

On the theoretical front, numerous advances in interpreting these EDM measurements have been performed. Detailed calculations of atomic EDMs using state-of-the-art many-body techniques, including the effects of octupole enhancements in deformed nuclei, are now available[130, 131]. New computations of the neutron and deuteron EDMs using lattice QCD[126–128], light front QCD[115], and effective theory methods[129] have also been performed. These calculations, alongside the development of theoretical methods for computing the baryon asymmetry, have sharpened the implications of EDM measurements and dark matter searches in testing electroweak baryogenesis. At the same time, there exist important opportunities for future theoretical progress. In particular, new computations of the so-called "nuclear Schiff moment" are needed, in light of a recent reformulation of

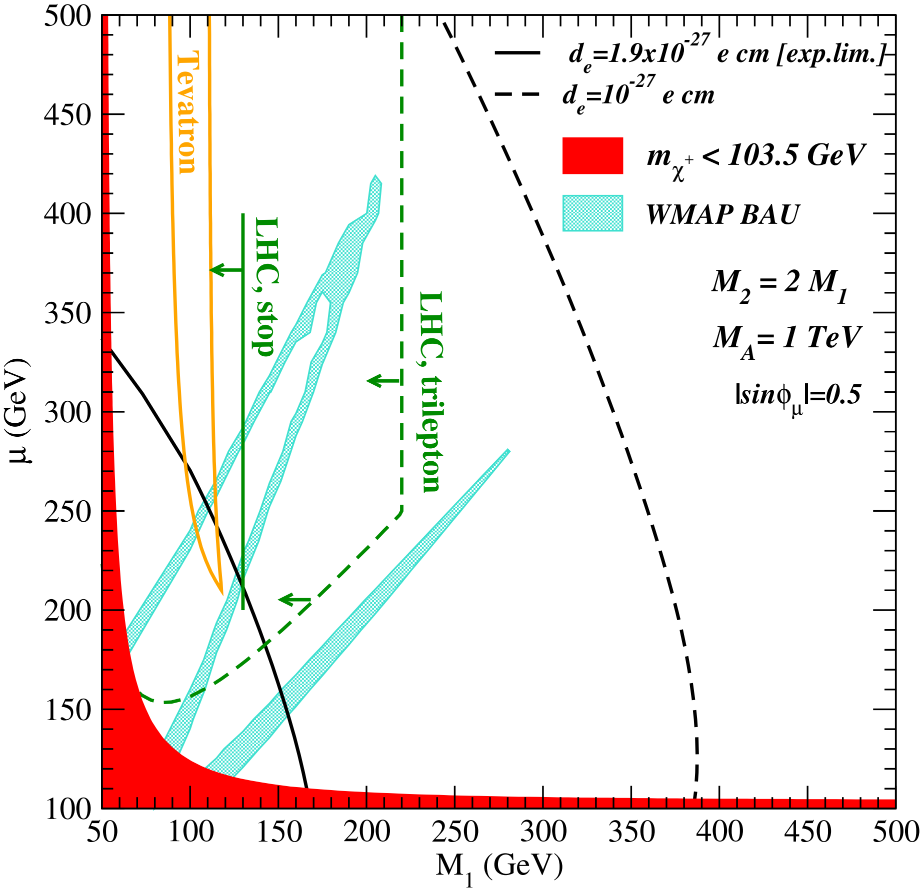

FIG. 2: Illustrative sensitivity of present and future EDM measurements to supersymmetric mass parameters relevant for electroweak baryogenesis. The vertical axis gives the supersymmetric Higgs/Higgsino mass, while the horizontal axis gives the $U(1)_Y$ gaugino mass parameter M_1. The light blue regions indicate the regions for these masses needed to obtain the observed baryon asymmetry. The red region is excluded by LEP. The region toward the origin from the solid red line is excluded by the present electron EDM limit, while the dashed line gives prospective future d_e sensitivity. The reach of the neutron EDM is similar. Light yellow and green lines indicate sensitivity of future direct search measurements at the Tevatron and LHC. (Figure adapted from Ref. [88])

the way atomic electrons screen out the interaction of a nuclear EDM with an applied external electric field. A systematic analysis of the theoretical uncertainties in neutron, nuclear, and atomic EDM computations should also be carried out. Similarly, there remain both formal and phenomenological issues in computing the baryon asymmetry in models of new CP violation and relating the relevant parameters to EDMs of various systems. Realizing the full impact of potentially revolutionary discoveries of new CP violation in

EDM experiments requires corresponding continued theoretical progress.

C. Neutrino Physics Goals and Opportunities

The search for neutrinoless double beta decay is but one of a set of important measurements aimed at an understanding of the neutrino and its role in physics, cosmology, and astrophysics.

Neutrino oscillations have been observed in atmospheric, solar, reactor and accelerator neutrino experiments, the mass-squared differences have been determined and the mixing angles measured. These fundamental observations indicate that neutrinos do indeed have mass, and that flavor mixing is very substantial. The Standard Model does not predict these effects, and a new theoretical construct is called for. Our new understanding of neutrinos has forced us to add at least seven new parameters (nine if neutrinos are Majorana particles) to the already parameter-laden Standard Model. Of these, only five are needed to describe every confirmed neutrino physics result. The new neutrino sector therefore remains largely unexplored.

The neutrino sector seems to consist of three active species that mix strongly. The mass eigenstates and flavor eigenstates are connected by a unitary transformation:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The matrix $\mathbf{U}$ is the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix. The oscillation experiments define two mass-squared differences, Δm^2_{12} and Δm^2_{23}, but only the level ordering of ν_1 and ν_2 is experimentally known, from solar neutrino experiments in which the flavor conversion is matter enhanced via the Mikheyev-Smirnov-Wolfenstein effect. This leads to two possible scenarios for the neutrino mass spectrum, as illustrated in Fig. 3.

While the mass-squared differences are fairly well determined, the overall scale of the masses remains quite uncertain. It is bounded from below by the oscillation data and fact that no mass can be less than zero. This leads to an average neutrino mass (the quantity of cosmological interest) of at least 20 meV. Small as that may seem, neutrinos nevertheless outweigh luminous stars in the universe. The upper end of the mass scale is a hundred times larger, bounded by direct mass measurements based on the beta decay of tritium. The average mass is experimentally known to be less than 2.2 eV. Cosmology itself yields a somewhat model-dependent upper limit from the galaxy correlation function and the Lyman-α forest of about 0.2- 0.5 eV for the average mass. There is an opportunity for very interesting comparisons if the laboratory and cosmological mass sensitivities can be simultaneously improved.

1. Single Beta Decay

There is US participation in the design of the KATRIN tritium beta decay experiment [42] to make a kinematic determination of the neutrino mass by a detailed study of the

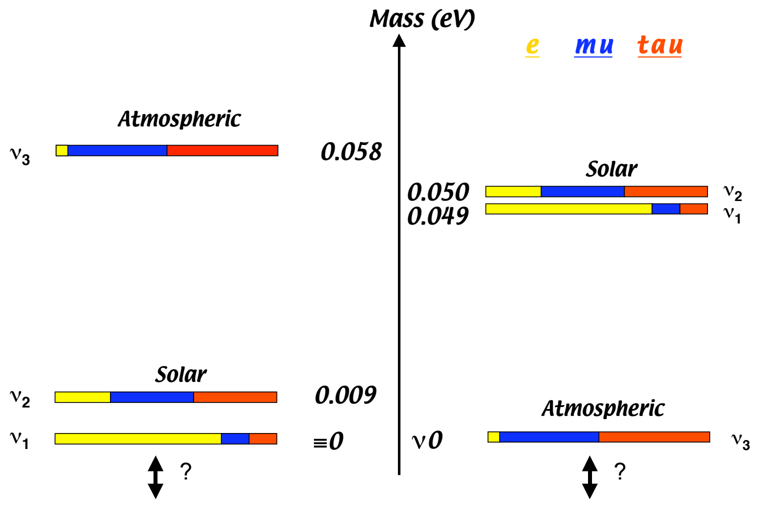

FIG. 3: Normal (left) and inverted (right) hierarchies for the neutrino mass spectrum. The spectra shown apply only when the mass of the lightest eigenstate is zero, but the "offset", or absolute mass, is only known to be less than 2.2 eV.

shape of the beta spectrum near the endpoint. If the masses are greater than about 0.1 eV, all 3 eigenstates have essentially the same mass, and the term 'the neutrino mass' can be used without loss of generality. KATRIN will be able to discover a 0.35-eV mass at 5 σ, or rule out a mass above 0.2 eV at the 90% CL. Figure 4 shows the spectrometer tank for the KATRIN tritium beta decay experiment on its way to Karlsruhe. The work is supported by a DOE operating grant, and DOE intends to provide equipment funding at the $3 M level. R&D to develop the NEXTEX project [43], also a tritium experiment, has been supported through 2005 by NSF, and a construction request for $6M has been submitted. NEXTEX would be able to rule a mass of 0.8 eV at the 90% CL. Two independent groups in Italy at Genoa and Milan are pursuing a ^{187}Re experiment, and there is planned US involvement. Once the appropriate technology has been selected, a large project, MARE, will be jointly developed [44]. The ultimate sensitivity for MARE will depend on the outcome of the R&D program, but to reach below 0.2 eV, the ultimate limit of KATRIN, is not out of the question.

2. Hierarchy

Not only is the absolute mass scale of the neutrinos unknown, but so also is the ordering of these masses. The electron neutrino is composed largely of the 2 closely-spaced mass eigenstates. Is the third mass eigenstate the heaviest or the lightest of the three? These possibilities are referred to as the normal or the inverted hierarchy. Although it seems natural that the lightest neutrino would be strongly associated with the lightest lepton (the electron), the question is still open. If the absolute mass scale is large compared to the mass splittings implied by the oscillation experiments, then all the mass eigenstates

FIG. 4: The 10-m diameter tank for the KATRIN spectrometer moving through the town of Leopoldshafen on the Rhine, on its way to the Forschungszentrum Karlsruhe. The objective of the tritium beta decay experiment is a sensitivity to mass at the 200-meV level.

are nearly the same. In this case, the mass spectrum is quasi-degenerate. The hierarchy of the neutrino mass spectrum can best be addressed by oscillation experiments.

3. Mixing angles

What are the values of the weak mixing angles? Two are large and have been measured while the third, θ_{13}, is small and is only constrained to be less than 10^o. The values of these angles have important astrophysics and fundamental physics implications. In particular, CP violation is only measurable in neutrinos if θ_{13} is non-zero. The required better measurements of these angles can come from solar, reactor and accelerator neutrino oscillation experiments.

Direct measurements of θ_{13} are being attempted in antineutrino disappearance experiments at four reactor sites, as described below. Information on θ_{13} in combination with other information (the mass hierarchy, and CP-violation parameter δ) will come from long-baseline accelerator experiments T2K (Tokai-to-Kamioka in Japan [38]), MINOS (Main Injector Neutrino Oscillation Search at Fermilab [34]), and NOvA (Neutrino Oscillation at Fermilab [35]). The accelerator experiments will also produce more precise measurements of θ_{23} than are presently available from the atmospheric oscillation experiments (mainly

Super-Kamiokande) and from K2K (KEK-to-Kamioka [9]). MINOS is already in operation and has produced new contours for θ_{23} and Δm^2_{23}.

The angle θ_{12} is most precisely determined from solar neutrino data (SNO, SAGE, Gallex, Cl-Ar), with a less precise contribution from KamLAND. KamLAND, on the other hand, fixes the corresponding mass splitting Δm^2_{12} more precisely. Solar neutrino data also provides a modest constraint on θ_{13}, the effects of which are energy-independent, whereas the θ_{12} effects are matter-enhanced above a few MeV and can thus be distinguished.

Solar experiments aimed at precise determination of the neutrino spectrum below 5 MeV provide a means to search for small admixtures of sterile neutrinos with mass splittings down to 10^{-10} eV^2. Indeed, a variety of interesting scenarios in both neutrino physics and solar physics can be put to the test by making a direct confrontation between the solar luminosity measured electromagnetically and in neutrinos. A comparison at the 1% level is perhaps achievable. Since it is not possible to measure neutral-current neutrino interactions spectroscopically at these low energies, a key part of this program is precise knowledge of θ_{12}. At low energies, the suppression of the electron flavor is essentially directly proportional to $\cos^4\theta_{13}\sin^2 2\theta_{12}$ and can be determined by comparison of charged-current and elastic-scattering data. At higher energies, the suppression is further enhanced by matter effects, giving SNO its excellent sensitivity to this factor.

It is so customary to express the MNSP matrix in its unitary form with the three standard mixing angles, that it is easy to lose sight of the fact that the unitarity is a testable feature, just as it is with the CKM matrix. In essence, the solar luminosity comparison is such a test, because the unitary construction makes a precise prediction of the relationship between the measured flux in various flavors and the energy production in the sun. Agreement between those measurements is a prediction of unitarity and a a sun in quasistatic equilibrium.

Experiments on solar neutrinos are described in the next section.

4. Solar Neutrinos

The unraveling of the solar neutrino problem has now given us the opportunity to return to the original goal of solar neutrino measurements: understanding the nuclear physics responsible for the generation of the Sun's energy. After more than 35 years of effort, we can finally use neutrinos as a tool to study the Sun. The Borexino experiment [31] in Gran Sasso, is preparing to take solar neutrino data in 2007. KamLAND is being upgraded to operate in singles mode in order to detect solar neutrinos. Reduction of radioactivity burdens by factors of as much as 10^6 will be obtained with the help of a $6M distillation plant being installed. Data taking in the SNO experiment has been completed as of Nov. 28, 2006. Analysis of the data will continue for another 2 years. A scintillation detector, SNO+ [32], is proposed for the new underground laboratory SNOLAB. R&D for SNO+ is being provided by NSERC. The SNOLAB infrastructure has been funded with $39M CDN from CFI (Canada Foundation for Innovation). The SAGE gallium solar neutrino experiment in Russia continues to run, with new data being acquired with both solar neutrinos and sources of ^{51}Cr and ^{37}Ar.

Work continues on a spectroscopic charged-current solar neutrino experiment, LENS [36], using indium-loaded scintillator, and on the CLEAN liquid neon concept [37], an elastic-scattering detector for the low-energy neutrino spectrum. Both of these experiments, and the geoneutrino experiment GNULAND (see below), could be sited at the DUSEL laboratory.

Other nuclear physics measurements are needed to fully understand solar neutrino experiments. Understanding the production rate of neutrinos from the decay of ^{7}Be and ^{8}B in the solar core is of crucial importance for fully capitalizing on the wealth of solar neutrino data from Super-K and SNO and that is expected in the near future from Borexino and KamLAND. While uncertainties in solar properties like the metallicity currently dominate solar model predictions of the ^{7}Be and ^{8}B neutrino flux, efforts in the astrophysical community are aimed at reducing these uncertainties, and uncertainties in the solar nuclear reaction rates continue to add significantly to the uncertainty in solar model predictions of these neutrino fluxes. Efforts during the last few years have improved our understanding of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction rate, and measurements are currently ongoing aimed at the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction rate. It is important that these efforts continue so that nuclear cross-sections can be eliminated as a substantial source of uncertainty affecting interpretations of solar neutrino measurements.

5. Reactor Neutrinos

Reactor neutrinos will continue to be an important source of information on the neutrino mixing matrix and mass spectrum. The KamLAND experiment continues to accumulate reactor and geoneutrino data as it prepares for its transformation to a solar experiment. The experiment has recently completed a full volume calibration that will enable a substantial reduction in the largest systematic error: the fiducial volume. Scintillator purification will soon be implemented to reduce backgrounds in the detector. These measures will enable KamLAND to reduce the systematic errors in determination of Δm^2_{12} and θ_{12}. In addition, KamLAND will acquire data for several more years as measurements of ^{7}Be solar neutrinos proceed.

Elsewhere, the future reactor program is focused on the determination of the last unknown mixing angle, θ_{13}. A non-vanishing value of this parameter is necessary for the existence of CP violation in the neutrino mixing matrix. Thus the establishment of a finite value of θ_{13} is the first step towards exploration of CP violation in the lepton sector. Leptonic CP violation is an important ingredient for the leptogenesis explanation of the matter-antimatter asymmetry in the universe. In addition, the value of θ_{13} is essential for understanding flavor-change effects in supernovae and subsequent r-process nucleosynthesis and for planning future long-baseline accelerator experiments.

Reactor antineutrino disappearance enables a clean determination of θ_{13} independent of CP-violation and matter effects, and is complementary to long-baseline accelerator experiments. It is, however, challenging to do a neutrino disappearance experiment at the $\sim 1\%$ level required. Four reactor θ_{13} experiments are being actively pursued: Angra in Brazil, Daya Bay in China, Double Chooz in France and RENO in South Korea. A detailed quantitative discussion of the θ_{13} reach of these four experiments is presented by Mention *et al.* [33]. Sensitivities depend on assumed systematic errors, backgrounds, run times, and reactor power assumptions, in addition to detector layout as proposed. The 90% CL limits on $\sin^2 2\theta_{13}$ are calculated for Double Chooz (0.0278), Daya Bay Mid with Ling Ao II off (0.0410), Daya Bay Mid with Ling Ao II on (0.038), Daya Bay Far (0.011) and RENO (0.0213). Completion dates are not specified.

Both CHOOZ [41]and Daya Bay [118] have US participation. The large US component of the Daya Bay collaboration includes several nuclear physics groups with key expertise and experience from KamLAND and SNO, although US capital equipment funds will be provided by DOE-HEP, and R&D funding is also being provided from that source. DOE-NP has a long (almost 30 years) and successful history of supporting reactor neutrino research (ILL, Gösgen, PaloVerde, KamLAND). The relevant previous experience in the Daya Bay collaboration from KamLAND and SNO resides primarily in groups funded by nuclear physics (the US Daya Bay collaboration contains 13 institutions, of which 6 receive funding from nuclear physics).

6. Geoneutrinos

Future geoneutrino experiments would allow us to directly determine the amount and location of heat generation in the Earth, which will provide a strong constraint on mantle convection models and Earth formation models. They would also allow us to test the fundamental assumption in Earth formation models that the uranium and thorium ratio is well determined due to the similar properties of these elements, the ratio of these elements. These are fundamental questions to our understanding of the Earth and are of greatest importance to geology. These questions will be answered by nuclear physicists, who have the necessary expertise to perform these neutrino measurements.

7. Unitarity of MNSP and sterile states

Are there light sterile neutrinos? The LEP results on the width of the Z boson indicate that there are 3 neutrinos that couple to the Z boson, so-called active neutrinos. The see-saw mechanism would produce 3 light active neutrinos and 1-3 very heavy sterile neutrinos. If there are light sterile neutrino states that mix with the 3 active neutrinos, the mixing matrix that describes the superposition would no longer be unitary when viewed in a 3x3 context. The unitarity of the mixing matrix can be tested through oscillation experiments. Indications for a sterile neutrino from the LSND experiment are not supported by the recently reported results from MiniBooNE. Other approaches to the question of light steriles admixed with the electron neutrino include precise comparison of the solar electromagnetic luminosity with the neutrino luminosity, and the use of an intense radioactive source as a 'standard candle' with a large detector, such as LENS.

8. Accelerator Neutrinos

The MiniBooNE experiment looking for electron neutrino appearance in the muon neutrino beam from the Fermilab 8 GeV Booster has completed its running with neutrinos and is now taking antineutrino data. First results were reported April 11, 2007, and do not confirm the 1990s observation of this conversion by LSND. The MINOS long-baseline experiment has begun its research program, and there is considerable US involvement in the T2K long-baseline experiment in Japan [38]. Both are funded by DOE HEP. Super-Kamiokande, recently refurbished with new PMTs, is in operation collecting solar and atmospheric neutrino data, and preparing to receive the neutrino beam from J-PARC. The first neutrinos from CERN have recently been detected in the OPERA experiment [39, 40] at Gran Sasso. The intense flux of neutrinos from SNS presents opportunities for neutrino oscillation searches there.

9. Cross-sections and Nuclear Effects for Oscillation Analysis

The primary detection channel for beam and atmospheric neutrino oscillation experiments is charged-current quasi-elastic scattering on nuclei; the flavor of the outgoing lepton is tagged, and flavor content compared before and after neutrino propagation. Typical targets are oxygen, carbon, argon and iron. Additional channels, *e.g.* charged and neutral current single- and multi-pion production, are important for oscillation experiments as well; they can feature as either background or signal.

Although one can often obtain powerful cancellation of uncertainties by comparing measurements in near and far detectors, there will always be systematic differences between near and far detector measurements –in terms of both detector properties and, in particular, neutrino spectra– which limit the effectiveness of this technique. A different energy distribution of incoming neutrinos in the near and far detectors, due to oscillation effects, convoluted with unknown energy-dependent cross sections and nuclear effects, can limit eventual precision. Therefore detailed knowledge of neutrino-nucleus interactions is highly desirable. 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. Even the relatively simple quasi-elastic channel is not perfectly characterized. Charged and neutral current pion production, which comprise a fairly large portion of neutrino data sets in this energy regime, are even less well understood and represent a serious background to forthcoming θ_{13} searches. There are existing indications of discrepancies between theory and data: for instance, K2K has recently measured anomalously low coherent charged current single-pion production. Clearly more information is needed. Nuclear effects, *i.e.* absorption or rescattering interactions of products of the primary neutrino-nucleon interaction with nuclear matter, can also have significant effects on the observed energy of the final states, and thus on the measured value of Δm^2.

10. Other Neutrino Properties

Do neutrinos have magnetic moments? Neutrino mass implies that neutrinos have a small magnetic moment if neutrinos have a Dirac mass. In that case, Standard Model interactions give the neutrino an anomalous magnetic moment of $3 \times 10^{-19}(\mathrm{m}_\nu/\mathrm{eV})$ Bohr magnetons, although beyond-the-Standard-Model interactions could give the neutrino a larger magnetic moment. A Dirac neutrino can have a static magnetic moment, whereas Majorana neutrinos can only have a transition magnetic moment connecting different mass eigenstates. Naturalness arguments and the scale of m_ν imply the existence of upper bounds on the magnitude of such magnetic moments, so the observation of a neutrino magnetic moment at a level just below the present experimental bounds would provide valuable information for understanding the neutrino mass mechanism. Experimental techniques for investigating magnetic moments includes studies at reactors, a tritium source, and the use of beta beams.

Are there non-standard interactions of neutrinos with matter? If so, this would lead to modifications of the matter effects in oscillation experiments. Studies of the transition of the oscillation effects in solar neutrinos as they shift from vacuum oscillations at low energies to matter oscillations at high energies can constrain such additional interactions.

Are there unexpected neutrino properties or interactions? Such properties might include violation of the equivalence principle or Lorentz invariance. There could be violation of CPT invariance or non-universal gravitational couplings. These would also appear as oscillation effects but with a departure from the classic oscillation wavelength energy dependence ($\lambda = \frac{4\pi E}{\Delta m^2}$).

Mass-varying neutrinos have been proposed as the explanation of what otherwise appears to be a curious coincidence. Why are the dark matter and dark energy densities comparable today even though their ratio scales as $1/a^3$ (a is the scale factor)? The coincidence that the scale of dark energy (2×10^{-3} eV) is similar to the scale of neutrino mass splitting (0.01 eV^2) was applied recently to this puzzle. Neutrinos can thus possibly be coupled to dark energy by supposing that the dark energy density is a function of neutrino mass and imposing the condition that the total energy density of neutrinos and dark energy remain stationary under variations of the neutrino mass. Then neutrino masses vary in such a way that the neutrino energy density and the dark energy density are related over a wide range of a. A simple way to make the dark energy density neutrino mass dependent is to introduce a Yukawa coupling between a sterile neutrino s and a light scalar field ϕ called the acceleron that couples to both neutrinos and matter. In this case it may be possible to test the scenario via neutrino oscillations since the effective neutrino mass is altered by the interactions via the scalar which in turn modifies ordinary matter oscillations of neutrinos. Application of these ideas to solar neutrinos shows that the survival probability P_{ee} can produce a higher-than-vacuum value (in the standard LMA scenario) at low energies, changing to LMA values of P_{ee} at high energies as measured in ^{8}B neutrinos. In between, P_{ee} lies systematically below the LMA profile of P_{ee}. The latter effect is similar to that via NSI (see above) however, the signature effect of mass varying neutrinos is the prediction of a higher than LMA pp flux.

D. Precision Measurements of Standard Model Properties: Overview

High precision electroweak experiments provide stringent tests of the Standard Model (SM) at the tree and quantum loop levels. A deviation from expectations would be indirect evidence for 'new physics' such as a heavy fourth generation of fermions, supersymmetry, extra dimensions, Technicolor, compositeness or other appendages to the known elementary particle spectrum and its interactions. In that way, precision studies complement high energy collider efforts, where we expect to unveil new phenomena directly. Furthermore, in some scenarios, precision measurements may be sensitive to physics at scales of O(1000 TeV), well beyond feasible direct collider capabilities.

Precision measurements span a broad range of physics sub-disciplines, including atomic, nuclear and high energy physics. Nuclear physics experiments are often well matched to precision studies because the techniques or needed facilities fall under the nuclear realm. An example is the search for a violation of electron-muon weak charged current universality in $\pi_{\ell 2}$ decays $[\pi^+ \to \ell^+\nu(\gamma),\ \ell = e, \mu\ ]$. The ratio

$$R_{e/\mu} = \frac{\Gamma[\pi^+ \to e^+\nu(\gamma)]}{\Gamma[\pi^+ \to \mu^+\nu(\gamma)]} \tag{1}$$

is very precisely predicted in the Standard Model. Including, quantum corrections, one expects $R_{e/\mu} = 1.2353(4) \times 10^{-4}$. The small uncertainty ($\pm 4 \times 10^{-8}$)stems from hadronic loop effects. It could probably be reduced further by additional theoretical work. That prediction is to be compared with relatively old experimental results [64] from TRIUMF and PSI (meson laboratories in Canada and Switzerland) $R_{e/\mu} = 1.2310(40) \times 10^{-4}$ The good agreement (about the one sigma level) constrains new axial and pseudoscalar interactions that violate e-μ universality at the 10-500 TeV level. Planned experiments at both TRIUMF and PSI will improve $R_{e/\mu}$ by a factor of 5 or better and thereby probe yet higher mass scales.

Besides leptonic pion decays, there are other fundamental precision measurements that fall partly or entirely under the domain of nuclear physics. Here, we concentrate on three exciting forefront programs: 1) β-decay tests of CKM unitarity and searches for non-$(V - A) \otimes (V - A)$ interactions; 2) determinations of the weak mixing angle $\sin^2 \hat{\theta}_W$ and 3) muon physics, particularly the muon anomalous magnetic moment which may already be giving strong hints of supersymmetry. All three topics could be pushed further at nuclear physics facilities if properly supported.

1. β-decay

Unitarity of the three-generation quark mixing matrix requires for the first row

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad . \tag{2}$$

A deviation from unity would signal new physics such as additional heavy quark mixing, a violation of quark-lepton universality, heavy new gauge bosons, and effects of supersymmetry or extra dimensions, etc. Indeed, uncovering a real deviation would have profound implications. Of course, even confirming unitarity at the fraction of a percent greatly constrains what new physics is allowed in speculations that go beyond the SM.

Since $V_{ub}^2 \approx 1 \times 10^{-5}$ is tiny, this unitarity test finds itself in the realm of relatively low-energy physics. Indeed, V_{ud} in particular has traditionally been obtained by comparing nuclear $0^+ \rightarrow 0^+$ superallowed β-decay with muon decay, a purely leptonic reaction while V_{us} has come from kaon and hyperon decays, an interface area between nuclear and particle physics.

For some time, a persistent violation of CKM unitarity seemed to be present, even after electroweak radiative corrections were carefully included. Roughly, one found $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9965(15)$; a tantalizing 2.3 sigma deviation from unity that could be either considered a great success of SM radiative corrections (without those quantum effects, one finds 1.03) or a hint of new physics. The general feeling during that time period was that $V_{ud} = 0.9736(5)$ was likely to be wrong and that eventually it would increase to about 0.9756 as suggested by unitarity. However, due largely to the persevering efforts of J. Hardy and I. Towner [65] (for which they received the 2006 Bonner prize in nuclear physics), to improve the nuclear theory and experimental input, the value of Vud has remained very stable. In addition, recent improvements of the electroweak radiative corrections [66] to nuclear β-decays have reduced the theoretical uncertainty. Currently, one finds by averaging the nine best superallowed nuclear β-ecays [67]:

$$V_{ud} = 0.9737(2)(2), \tag{3}$$

where the first error comes from experiment and nuclear theory while the second error stems from hadronic uncertainties from electroweak radiative corrections. With additional theoretical work, the latter may be further reduced. Although it will be difficult to significantly improve the nuclear physics uncertainty, it is extremely important to further scrutinize the nuclear corrections and re-measure transition rates and Q values for as many nuclei as possible in order to confirm their correctness and consistency.

A much more dramatic effect recently occurred in the extraction of V_{us} from $K_{\ell 3}$ decays ($K \rightarrow \pi \ell \nu$, $\ell = e$, μ). A series of high statistics experiments at BNL, FNAL, CERN and Frascati essentially rewrote the PDG book [64] on kaon physics. In the process, they found about a 5% increase in the $K_{\ell 3}$ branching ratios, leading to the (very recent) average (which includes some preliminary data) [68]

$$V_{us} = \frac{0.2162(4)}{f_+(0)} \tag{4}$$

where$f_+(0)$ is the vector current form factor that deviates from 1 due to SU(3) breaking effects. Recent preliminary lattice results[69] give $f_+(0) = 0.9609(51)$. That value leads to $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9988(6)(6)$ with roughly equal uncertainties steming from V_{ud} and V_{us} [mainly via $f_+(0)$]. Unitarity is confirmed at about the 1.4 sigma level or ±0.1%, a triumph for the Standard Model at the level of its quantum loop corrections. Used as a constraint, that finding limits effects of additional heavy quark or lepton mixing to less than about 3% and charged gauge bosons to greater than several TeV. It also constrains loop corrections due to supersymmetry, Z' bosons, extra dimensions *etc.*

Further improvement in the CKM unitarity test will require reduction in the uncertainty of both V_{ud} and V_{us}. A reduction factor of about three in the V_{us} error may be possible with additional lattice work on $f_+(0)$ or by employing $K_{\ell 2}$ decays and lattice calculation of f_K, the kaon decay constant. To improve V_{ud} will require additional theory work on radiative corrections as well as measurements that test the nuclear theory input. Alternatively, one can change the experimental approach and consider simpler beta decay systems.

In principle, one could measure V_{ud} using the more theoretically pristine pion β-decay ($\pi^+ \to \pi^0 e^+ \nu$) rate. Indeed, a heroic effort at PSI has measured that rate with better than 1% precision. However, because of the small branching ratio (10^{-8}), it would be very difficult to reach a level competitive with superallowed nuclear decays.

The only realistic way to improve V_{ud} is via neutron decay. By measuring the neutron lifetime, τ_n, and g_A (using decay asymmetries), one can obtain V_{ud} from [66]

$$|V_{ud}|^2 = \frac{4908.7(1.9)\,\mathrm{sec}}{\tau_n(1+3g_A^2)} \quad , \tag{5}$$

where the error stems from hadronic loop uncertainties. That error may be further reduced by additional theoretical scrutiny.

Currently, there are serious experimental discrepancies in the determinations of both τ_n and g_A, making the extraction of V_{ud} unreliable[70]. However, with the advent of several new more intense neutron facilities, τ_n and g_A measurements are both expected to be significantly improved. Combined with continuing improvements in the electroweak radiative corrections, it may be possible to obtain Vud to about 0.015% precision and test CKM unitarity to about the 0.04% precision level; thereby confronting the current discrepancy with 5 sigma sensitivity. Testing unitarity at that level without nuclear uncertainty will provide either powerful evidence for or constraints on new physics.

In addition to testing the unitarity of the CKM matrix, one may exploit β-decay to search for evidence of interactions that depart from the $(V-A)\otimes(V-A)$ structure of the charged current weak interaction. The possibilities for such departures can be described by the effective Lagrangian

$$\mathcal{L}^{\beta-\mathrm{decay}} = -\frac{4G_\mu}{\sqrt{2}} \sum_{\gamma,\,\epsilon,\,\delta} a^{\gamma}_{\epsilon\delta}\ \bar{e}_\epsilon \Gamma^\gamma \nu_e\, \bar{u} \Gamma_\gamma d_\delta \tag{6}$$

where the sum runs over Dirac matrices $\Gamma^\gamma = 1$ (S), γ^α (V), and $\sigma^{\alpha\beta}/\sqrt{2}$ (T) and the subscripts δ and ϵ denote the chirality (R,L) of the d-quark and outgoing β particle, respectively. In the SM, one has $a^V_{LL} = V_{ud}$ at tree level and all other $a^\gamma_{\epsilon\delta} = 0$. Studies of β-decay correlations can be used search for evidence of departures from these SM expectations that may arise in various models for new physics. In models with right-handed gauge bosons, for example, one has the possibility that a^V_{RR}, a^V_{LR}, and a^V_{RL} are non-zero at tree-level, while supersymmetric radiative corrections can induce non-vanishing scalar and tensor operators at loop level. Considerations of neutrino mass also lead to expectations for the a^V_{LR} and a^V_{RL}, and a comparison of these expectations with the results of direct experimental β-decay constraints provide a unique probe of models for neutrino mass generation.

Experimentally, studies of neutron and nuclear β-decay probe these interactions by focusing on one or more of the possible decay correlations appearing in the partial rate:

$$\begin{aligned} d\Gamma \propto \mathcal{N}(E_e)\Bigg\{ & 1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{\Gamma m_e}{E_e} + \langle\vec{J}\rangle\cdot\left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right] \\ & +\vec{\sigma}\cdot\left[N\langle\vec{J}\rangle + G\frac{\vec{p}_e}{E_e} + Q'\hat{p}_e\hat{p}_e\cdot\langle\vec{J}\rangle + R\langle\vec{J}\rangle\times\frac{\vec{p}_e}{E_e}\right]\Bigg\}d\Omega_e d\Omega_\nu dE_e, \end{aligned} \tag{7}$$

where $N(E_e) = p_eE_e(E_0 - E_e)^2$, E_e (E_ν) and $\vec{p}_e$ ($\vec{p}_\nu$) are the β (neutrino) energy and momentum, respectively; E_0 is the endpoint energy; and $\vec{J}$ is the polarization of the decaying nucleus, $\vec{\sigma}$ is the β polarization, and $\Gamma = \sqrt{1-(Z\alpha)^2}$. The coefficients of the various correlations involving lepton momenta and nuclear spin depend on the structure of the underlying lepton-quark weak interaction. The correlations parameterized by A, B, and G are odd under parity (P) and even under time-reversal (T); the D-term is T-odd but P-even; the R correlation is both T- and P-odd; and all others are P and T-even. For example, the "Fierz interference" coefficient b and the E_e-dependent part of the PV neutrino correlation parameter B can probe the SUSY-induced scalar and tensor interactions[88]. Current limits on b from superallowed nuclear decays places limits on these interactions at the $\sim 10^{-3}$ level.

As described below, a new generation of neutron decay studies at the SNS, NIST, and LANSCE will provide an opportunity to perform a comprehensive search for non- $(V-A)\otimes(V-A)$ interactions with measurements of a number of neutron decay correlations. These searches are quite complementary to those that will be performed at the LHC. Together with the opportunity to reconcile current disagreements in τ_n and g_A among neutron decay experiments –thereby providing an improved test of CKM unitarity – this opportunity provides a compelling case for the next generation of neutron decay experiments. Together with a full agenda of other neutron studies such as radiative neutron decay – for which there have been recent theoretical advances[114] – searches for CP violation etc. and of course the flagship neutron electric dipole moment searches, a rich program of neutron experiments is possible.

2. The Weak Mixing Angle: $\sin^2\hat{\theta}_W$

The weak mixing angle, θ_W, parametrizes the mixing between neutral SU$(2)_L$ and U$(1)_Y$Y gauge bosons in the Standard Model. It is, arguably, the most important parameter in electroweak physics. When combined with precision measurements of α, G_F (the Fermi constant) and M_Z, it can be used to probe quantum loop corrections from heavy fermions, the Higgs scalar, and various new physics effects. Indeed, it was used to predict the heavy top quark mass before its discovery. Now that we know $m_t = 171.4(2.1)$ GeV rather precisely, it is employed to constrain the Higgs mass, m_H.

A global fit to all Z pole properties[64] currently indicates $\sin^2\hat{\theta}_W(M_Z) = 0.22125(16)$ (where the "hat" indicates the quantity renormalized in the $\overline{MS}$ scheme) which corresponds to

$$m_H = 100^{+40}_{-30} \text{ GeV} \quad . \tag{8}$$

Combined with the direct experimental search constraint $m_H = 114.4$ GeV, that result is suggestive of a relatively light Higgs (115-140 GeV), in keeping with supersymmetry models. In fact, that consistency check is often used as indirect evidence for supersymmetry.

Unfortunately, the χ^2 of the $\sin^2\hat{\theta}_W(M_Z)$ pole fit is not very good. In fact, the two best measurements, A_{LR} using polarized $e^+e^- \to Z$ production and $A_{FB}(Z \to b\bar{b})$ differ by about 3.4 sigma. A_{LR} gives $\sin^2\hat{\theta}_W(M_Z) = 0.23070(26)$ which on its own implies $m_H = 30^{+30}_{-18}$ GeV in the SM context and is already ruled out. On the other hand, $A_{FB}(Z \to b\bar{b})$ implies $\sin^2\hat{\theta}_W(M_Z) = 0.23193(29)$ which corresponds to a very heavy Higgs, $m_H = 400^{+300}_{-190}$ GeV, but is in conflict with W mass measurements. If it were to be correct, $A_{FB}(Z \to b\bar{b})$ could be interpreted as evidence for heavy-fermion loop effects from additional quark-lepton generations or Technicolor. Clearly, the true value of $\sin^2\hat{\theta}_W(M_Z)$ needs to be known with much better certainty than is currently the case.

Within the context of the SM, low Q^2 experiments can also be used to determine $\sin^2\hat{\theta}_W(M_Z)$. Deriving a value for this parameter at high energy scales from a low-energy measurements requires using the SM prediction for the evolution of this parameter, shown below:

Currently, the best such low-energy measurement comes from polarized e^-e^- (Moller) scattering at SLAC. Fixed target experiment E158 found

$$\sin^2\hat{\theta}_W(M_Z) = 0.2330(14) \quad \text{(Moller)} \quad . \tag{9}$$

Its uncertainty is not directly competitive with Z pole studies. However, it is very complimentary because various new physics effects, such as Z' or H^{--} bosons could enter into Moller scattering but not be observable at the Z pole. So, for example, comparing the Moller and Z pole values gives the rather restrictive bound on the Z_χ neutral gauge boson of SO(10) GUT models $Z_\chi > 1$ TeV. For comparison, direct searches for Z_χ at the Tevatron $p\bar{p}$ collider currently yield[64] $Z_\chi > 690$ GeV. If a Z boson is revealed at the LHC, low energy polarized electron scattering experiments could tell us something about its properties, if very high precision is attainable.

Studies indicate that improvements in low energy determinations of $\sin^2\hat{\theta}_W(M_Z)$ are possible using the high intensity polarized electron beam at JLAB. These studies were the subject of two workshops held at JLAB in December 2007 [104]. An approved experiment, Q-Weak will measure and determine $\sin^2\hat{\theta}_W(M_Z)$ to ±0.0008. It will also develop the polarimetry infrastructure that can be used throughout its future precision polarized electron scattering program. In the longer term, with a 12 GeV upgrade, it could measure $\sin^2\hat{\theta}_W(M_Z)$ in deep-inelastic eD and ep scattering. However, for really high precision, the polarized Moller asymmetry appears most promising. A ±0.00025 sensitivity in $\sin^2\hat{\theta}_W(M_Z)$ seems possible. (A factor of more than 5 improvement over E158.) At that level, one is competitive with the best Z pole measurements.

A clear deviation from Z pole results would be indicative of new physics. Such a measurement would be timely and important even after the LHC has made its first phase of

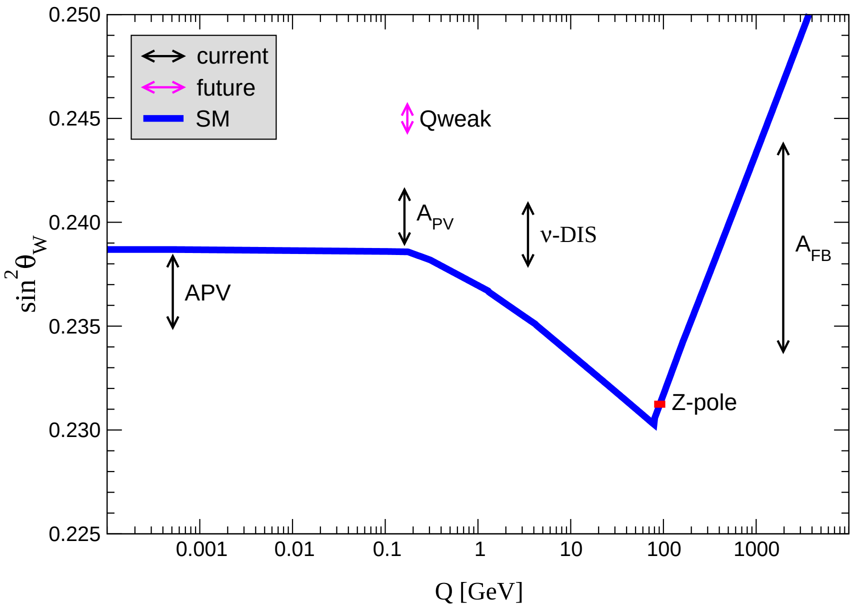

FIG. 5: Calculated running of the weak mixing angle in the SM, defined in the $\overline{\text{MS}}$ renormalization scheme[74]. Also shown are the experimental results from atomic PV, neutrino-nucleus deep inelastic scattering (ν-DIS), the parity violating asymmetry measurement at E158 (A_{PV}), the expected precision of Qweak and the lepton forward-backward asymmetry measurement at CDF (A_{FB}). This plot is taken from Ref.[89].

discoveries. If supersymmetry is discovered at the LHC, for example, the results of low energy measurements could be used to help determine important aspects of supersymmetric interactions with Standard Model particles. As illustrated below, supersymmetric loop effects as well as tree-level R-parity violation (RPV) interactions can cause deviations of the weak charges of the proton and electron from the Standard Model expectations in a highly correlated manner.

3. Muon Physics

Precision muon physics studies have a rich tradition and many results have been obtained since the last Long Range Plan. For example, a program is underway by the TWIST Collaboration at TRIUMF to improve the Michel parameters of muon decay by an order of magnitude with the hope of seeing a deviation from SM expectations or using agreement to constrain new physics. Initial results [79] on ρ, δ and $P_\mu\xi$ are all in agreement with the

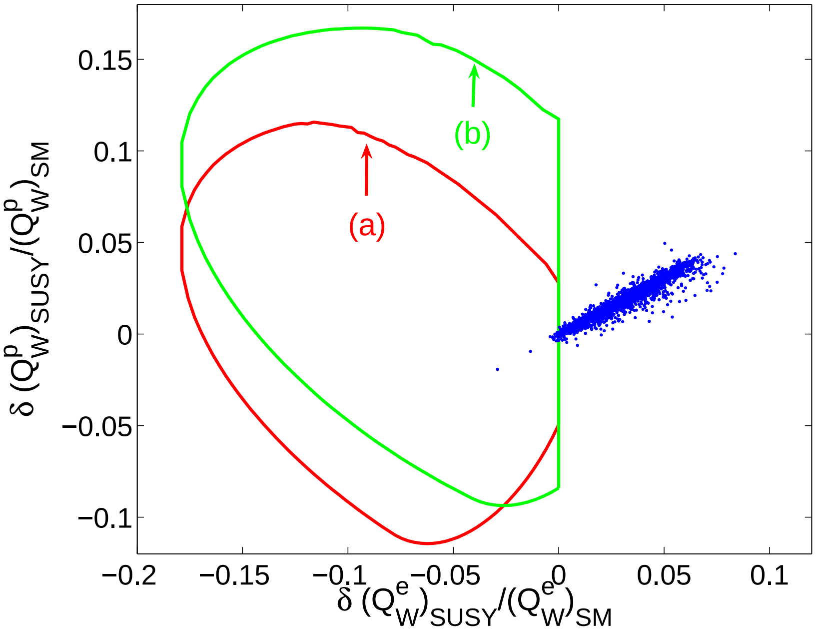

FIG. 6: Sensitivity of proton and electron weak charges to supersymmetry[75]. The dots represent the effects loop contributions in various supersymmetric models. The largest effects arise for large value of the $\tan\beta$ parameter, as favored by the deviation of the muon anomalous moment from the Standard Model expectations (see below). The interior of the elliptical regions indicate possible deviations due to RPV effects, which (a) and (b) corresponding to constraints depending, respectively, on whether CKM unitarity is not or is satisfied as discussed above. If R-parity is violated in supersymmetry, it is unlikely that the lightest supersymmetric particle can be a viable dark matter candidate. It would also imply that the neutrino is a Majorana particle.

SM, but at roughly threefold improved precision. Additional data are being analyzed.

The Fermi constant, G_F, measured via the μ^+ lifetime, will be improved by a factor of 20 at PSI. That parameter is used to normalize all weak charged current and most weak neutral current amplitudes. It is also instrumental for comparison with $\sin^2 \hat{\theta}_W(M_Z)$ and other precision electroweak measurements. An initial result [82] by the MuLan Collaboration yields $\tau_{\mu^+} = 2.197013(24)$ (11 ppm), which is 2.5 times more precise compared to any previous measurement. The updated Fermi constant is $G_F = 1.166372(6) \times 10^{-5}$ GeV^{-2} (5 ppm).

Another experiment (μCAP) in progress at PSI has made a measurement of the μ^- capture rate in hydrogen. Its initial result [81] yields a value $g_P = 7.3 \pm 1.1$ for the induced nucleon charged pseudoscalar coupling that is in good agreement with the prediction of chiral perturbation theory $g_p^{CHPT} \approx 8$. The MuCap technique yields an unambiguous interpretation and solves a long-standing problem in which earlier muon capture experiments seemed to give an unexplainable high value, $g_P^{\mathrm{exp}} \approx 12$.

Of all the recent muon experiments, the measurement of the muon anomalous magnetic moment, a_μ, by experiment E821 at BNL stands out both experimentally and theoretically. It found

$$a_\mu^{\mathrm{exp}} = 116592080(63) \times 10^{-11} \quad , \tag{10}$$

a factor of 14 improvement over the famous CERN experiments of the 1970s. The BNL measurement [83] was statistics limited and could be further improved. Indeed, an upgrade proposal by the $g_\mu - 2$ collaboration was approved by BNL as Experiment E969 [85]. It outlines a plan to reduce the error in a_μ^{exp} by more than a factor of 2.

Theoretical motivation for further improvement of a_μ^{exp} is compelling. In the SM, a_μ^{SM} is computable. Indeed, heroic efforts by many theorists have led to 5 loop calculations of QED contributions and 3 loop calculations of electroweak and hadronic effects making a_μ^{SM} perhaps the most theoretically scrutinized quantity in quantum field theory. At present, one finds the SM prediction [8]

$$a_\mu^{\mathrm{exp}} = 116591804(51) \times 10^{-11} \quad , \tag{11}$$

where the main uncertainty stems from hadronic loop effects. The 1st-order hadronic vacuum polarization (HVP) loop uncertainty is data driven—the HVP contribution is obtained from the absolute cross section of $e^+e^- \to$ hadrons, which is measured at numerous laboratories in different kinematic ranges. Because significant efforts are ongoing at KLOE, BaBar and Belle (in addition to the recent work by two experiments at Novosibirsk), the theory uncertainty from HVP to a_μ^{SM} will be reduced. The next largest uncertainty comes from hadronic light-by-light (HLbL) diagrams, which must be evaluated using a hadronic model. Efforts continue here and we anticipate that the nuclear theorists will be involved to help understand this contribution. Overall, one can expect that the theoretical uncertainty will reduce to about $\pm 30 \times 10^{-11}$. Such a reduction is well matched to the experimental goal of a future upgrade plan at BNL.

The current difference

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 276(63)_{\mathrm{exp}}(51)_{\mathrm{th}} \times 10^{-11} \tag{12}$$

represents an intriguing 3.4 sigma discrepancy. In fact, if it holds, it is arguably the strongest hint of new physics and demands further effort to increase the confidence in the result.

A popular new physics explanation is supersymmetry. One loop supersymmetry contributions to a_μ from gauginos and sleptons can naturally give the required 276×10^{-11} deviation noted above for supersymmetric particle masses in their anticipated 100-500 GeV mass range. The supersymmetry community watches Δa_μ very diligently and indeed an exhaustive review of the relation between the muon anomaly and supersymmetry has recently been written [84]. It describes the natural way in which the current magnitude of Δa_μ falls within, and discriminates between, many SUSY models.

Because of its chiral changing nature, the anomalous magnetic moment of the muon is particularly sensitive to supersymmetry loop effects. Moreover, determinations of Δa_μ can provide unique information about the supersymmetric parameters that are less readily obtained at the LHC. For example, the present value of Δa_μ favors a positive sign for the so-called "μ" parameter that determines the masses of the Higgs bosons and their superpartners in a supersymmetric world. Obtaining this sign information from collider searches that are typically sensitive to the magnitude (but not the sign) of new particle masses is quite difficult[1]. Another long recognized feature of the models is that the 1st-order SUSY loops couple approximately proportional to $(m_\mu/M_{\rm SUSY})^2 \tan\beta$ where $\tan\beta$ is the important ratio of vacuum expectation values in the two Higgs doublets. If, for example, the LHC establishes the mass of a SUSY candidate, the Δa_μ can, together with that mass, predict a $\tan\beta$. This quantity is very difficult to obtain from a collider and it is crucial in predicting other observables of the model. Thus, if supersymmetry is discovered at the LHC an even more precise measurement of a_μ – together with improvements in SM theory – will be critical for understanding the parameters of SUSY. In a similar vein, if the LHC uncovers evidence for some other new physics scenario, measurements of the muon anomalous moment will provide an important probe of its detailed character.

Exploiting the unique sensitivity of a_μ as much as possible by improving the experiment and SM theory is highly desirable, and it is unlikely that the expertise contained in the E821 collaboration can be reassembled if one delays a new measurement until after several years of LHC running. Nuclear scientists have played key roles in both the E821 measurement and are leading the new experiment, E969. Nuclear theorists are involved in sharpening the theoretical interpretation of a_μ through computations of hadronic contributions. Realizing the opportunity for achieving additional progress on both fronts will, therefore, require timely commitments from our field. Since operations of the AGS at Brookhaven fall under the domain of Nuclear DOE, further improvements in Δa_μ will likely require a commitment from the Nuclear Physics funding agencies.

We now amplify on these general remarks about the physics opportunities below:

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[1] If a particle is a Majorana fermion, such as the neutral Higgs boson superpartner, the mass term can have either sign.

E. Neutron Decay Studies

As discussed above, nuclear physics provides the most stringent test of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix via determinations of V_{ud} and V_{us}. While the most precise value of V_{ud} currently comes from superallowed nuclear β-decay, precision measurements of neutron decay parameters hold the most promise for improving the determination of V_{ud} in a system that is free of uncertainties due to nuclear structure. In addition, a comprehensive study of neutron decay correlation parameters can be used to search for non-$(V-A)\otimes(V-A)$ interactions with unprecedented sensitivity. The combination of improved calculations of radiative corrections, the availability of improved neutron sources, and the development of new experimental techniques has positioned this area for new results in the time frame covered by this plan.

Determination of V_{ud} from neutron decay requires precise determination of the neutron lifetime, precise determination of g_A/g_V from neutron decay correlations, and accurate calculation of the relevant radiative corrections. Three experimental techniques exist to determine the neutron lifetime: in-flight decay with cold neutron beams, production and trapping of ultracold neutrons in liquid helium by magnetic fields, and external production of ultracold neutrons and trapping in vacuum either by material walls or magnetic fields. The most precise in-flight beam measurement with a precision of 3.4 s has been made at NIST. The liquid helium technique is currently under development at NIST and will then move to the SNS Fundamental Neutron Physics Beamline (FNPB) where a precision of 0.15 s is expected. The vacuum technique has been used at the ILL with material walls to achieve a precision of 0.8 s. This result differs from the world average by 6.5 standard deviations. Future experiments will be required to resolve this very large discrepancy. The extension to magnetic confinement, which will not require correction for neutron losses due to wall interactions, is being developed at the LANSCE Ultracold Neutron (UCN) source and promises a precision at the 0.1 s level.

Determination of g_A/g_V comes from precision measurement of either the A, a, or C coefficient in neutron decay. The most precise determination of A is from the PERKEO collaboration at the ILL, using a reactor cold beam and reporting an uncertainty of 0.6%. The UCNA experiment at the LANSCE UCN facility expects to achieve a precision of 0.2% with very different systematics from the cold-beam measurements. This is the first decay correlation experiment to be performed with ultracold neutrons. Present measurements of a are not competitive, but the aCORN experiment planned for NIST expects to achieve 0.5%. The Nab and abBA series of experiments, being developed for the pulsed cold beam of the FNPB, expect to achieve precisions of approximately 0.1% for both A and a, and will also perform precise measurements of the B and b parameters. The PANDA experiment, proposed for the FNPB, expects to measure C with a precision of 0.1%. While the PERKEO series of experiments is expected to continue at ILL, the construction of the FNPB and fielding of these correlation experiments will position the US for leadership in this area.

While uncertainties in the calculation of radiative corrections in the neutron decay are not yet the limiting uncertainty, planned improvements in experiment promise to reverse this situation. Recent theoretical progress has reduced the uncertainty in the radiative corrections by approximately a factor of two. Further progress may be possible by formulating the problem in an effective field theory framework and calculating the required low energy constants on the lattice. The first measurement of neutron radiative decay branching ratio, performed at NIST, will provide a benchmark for similar calculations as it improves in sensitivity.

The three types of neutron sources suitable for precision neutron measurements, continuous cold beam, pulsed cold beam, and ultracold, are suited to different experimental methods. As these experiments are systematics limited, it is important to perform redundant experiments with different systematic vulnerabilities. It is therefore necessary for the field to have access to all three types of neutron sources. The NIST reactor provides the most intense beams of continuous cold neutrons in the US and an upgrade including a new moderator and guide hall is likely which will make the neutron flux comparable to ILL, the current world leader. While no DOE or NSF funds are required to operate this facility, support for researchers and equipment to conduct fundamental neutron experiments is needed. The SNS FNPB, funded by DOE Nuclear Physics and nearing completion, will provide the most intense pulsed cold beam in the world. Funding for a large electromagnetic spectrometer and detector packages for detecting neutron decay products is required for the planned correlation measurements. Flight path 12 at LANSCE, will continue to serve the community as a test and development pulsed cold beam that provides 1/2 the peak flux of the FBPB at 1/3 the rep rate. Ultracold neutrons are now being produced at the LANSCE UCN source, providing decay rates of 2 Hz for the UCNA experiment, with a factor of 10 improvement expected. Continued operation of this source, beyond the UCNA experiment, is needed to realize the opportunity for an improved neutron lifetime result and further measurements of the correlation coefficients (beyond the A coefficient) using ultracold neutrons.

As discussed above, precision studies of neutron beta decay parameters can also discover or place limits on non-$(V-A)\otimes(V-A)$ components to the weak interaction. Current limits on scalar and tensor contributions, from limits on the fierz interference term b in nuclear β-decays, are at the 10^{-2} level. A measurement of b in neutron decay is proposed as part of the Nab/abBA [61, 62] experiments at FNPB which can (statistically) improve upon this result. A similar measurement is being proposed with UCNs at LANSCE. Improved measurements of the neutrino-spin correlation B, also proposed by abBA to a statistical precision of 10^{-4}, and also possible with UCNs, can place limits on right-handed weak bosons or SUSY-induced scalar and tensor interactions. An improved measurement of the T-violating coefficient D to a precision of 2×10^{-4} is expected with a precision of 5×10^{-5} possible in the future.

F. Parity-Violating Electron Scattering

Thirty years ago, the study of weak neutral current interactions in fixed target polarized electron scattering played a central role in establishing the correct gauge structure of weak and electromagnetic interactions. The neutral weak amplitude was accessed by measuring the fractional difference in the cross-section for incident right- and left-handed electrons on an unpolarized target. A non-zero asymmetry is a signature of parity violation, and is dominated by the interference between the electromagnetic and weak amplitudes, mediated by photon and Z^0 exchange respectively.

Over the past two decades, giant strides in experimental technology have enabled experimental measurements of much greater precision, facilitating tests of the electroweak theory at the quantum loop level. Measurements of such precision are sensitive to new physics above the electroweak scale, in a manner complementary to direct searches at high energy colliders, as described already in Sec.IV D 2. Apart from constraining models of TeV scale physics, these measurements might play a critical role in disentangling the nature of anomalies in high energy collider data. In the following, we elaborate on past accomplishments and future directions in this class of experiments.

1. Recent Accomplishment: E158 at SLAC

The first PVES measurement with sufficient sensitivity to test the electroweak theory at the quantum loop level was the E158 experiment at SLAC [103]. For incident 48 GeV polarized electrons scattering off target electrons (Møller scattering) in a liquid hydrogen target, the parity-violating asymmetry was measured to be $(131 \pm 14 \pm 10)$ parts per billion (ppb). Within the context of the standard model, the value of the weak mixing angle at very low momentum transfer was obtained to be $\sin^2 \hat{\theta}_W(0) = 0.2397 \pm 0.0010 \pm 0.0008$, which established, to better than six standard deviations, the running of this fundamental parameter from the electroweak scale to low momentum transfer. Apart from setting important new constraints on new TeV scale physics, this measurement has demonstrated the technical feasibility of PVES to make asymmetry measurements with statistical and systematic errors at the ppb level.

2. Ongoing Project: Qweak at Jefferson Lab

A new project is under way at JLab to measure the parity-violating asymmetry in elastic electron proton scattering at very low momentum transfer [105]. The predicted asymmetry of about 200 ppb would be measured to a total accuracy of 4%, from which a low energy measurement of the weak mixing angle with a total precision of 0.0008 would be extracted. Quite apart from the improved test of the running of the weak mixing angle, this measurement is an important, independent probe of new physics at the TeV scale, with unprecedented sensitivity to new lepton-quark neutral current interactions.

The low energy phenomenological Lagrangian describing electron scattering off nucleons and nuclei is characterized by four coupling constants C_{1u}, C_{1d}, C_{2u}, and C_{2d}, depending on whether the hadron vertex is vector or axial-vector for each valence quark flavor. The Qweak measurement will make the worlds most precise determination of $2C_{1u} + C_{1d}$. Combined with the published measurement of parity violation in the 6S-7S transition in ^{133}Cs, independent and precise determinations of both C_{1u} and C_{1d} would be enabled. This provides complementary sensitivity to new TeV physics. Such a measurement would take on added significance should an anomaly be seen in the LHC data.

3. New Opportunities with the JLab Upgrade

Parity-Violating Deep Inelastic Scattering

While the C_{1q} couplings will be measured precisely, the C_{2q} couplings remain poorly constrained. This is because these couplings are much smaller in magnitude and they are difficult to access in elastic scattering. Parity-violating deep inelastic scattering (PVDIS) off an isoscalar target is sensitive to C_{2q}s, provided the measurements are made with sub-percent precision at kinematics where the scattered electron undergoes substantial energy loss. With the 11 GeV upgrade of JLab, sufficient luminosity at such kinematics will be available for the first time, which will enable precision PVDIS measurements at sufficiently high momentum transfer. The C_{2q} limits will broaden the sensitivity of low energy searches for new TeV scale physics, thus providing a more comprehensive set of constraints for analyses of LHC data.

In order to minimize the uncertainties in interpreting PVDIS measurements, it is important to ensure that nucleon structure at high Bjorken-x is well-understood and that the quark-parton description of the nucleon is appropriate. At the few percent level, issues such as charge symmetry violation and higher twist effects might introduce significant uncertainties. These topics are of long-standing interest in DIS physics. As described in the section entitled Weak Probes of Hadron Structure, these topics can be investigated after the energy upgrade at JLab with the aid of a new high-field, large volume solenoidal spectrometer [106]. The resulting constraints on nucleon structure would eliminate theoretical uncertainties in the extraction of the C_{iq}'s in PVDIS measurements.

Parity-Violating Møller Scattering

With Jefferson Laboratorys energy upgrade, the projected availability in beam energy and luminosity will enable the measurement of the weak mixing angle via parity-violating Møller scattering with a factor of 5 to 6 improvement over the published E158 data. The measurement would achieve the same level of precision as the measurements of the weak mixing angle on top of the Z resonance at electron-positron colliders. Since the two most precise measurements on the Z resonance disagree by more than three standard deviations, the measurement under discussion might shed light on this long-standing discrepancy. In addition, the sensitivity to new physics at the TeV scale would be unmatched by any other fixed target experiments until the advent of new high energy facilities such a Linear Collider or a Neutrino Factory.

G. Muon Physics

1. Muon Capture

Muon capture on the proton, $\mu + p \rightarrow n + \nu$ is of a similar fundamental nature as neutron beta decay. Because the momentum transfer is larger, muon capture is sensitive to additional, induced form factors. In particular, it is the most direct probe of the pseudoscalar form factor g_P, which is the least well known of all form factors characterizing the QCD structure of the nucleon in charged current reactions. Advances in modern effective field theories (heavy baryon chiral perturbation theory) allow the systematic calculation of g_P up to two-loop order. As this precise theoretical result is founded on basic concepts of chiral symmetry breaking, its experimental verification is considered a fundamental test of QCD at low energies. However, in spite of efforts spanning the last 40 years, the experimental situation remained inconclusive. Experiments lacked sufficient precision, due to the technical challenges involved, and, even more strikingly, could not be interpreted with confidence, as the formation of muonic molecules in high-density LH2 targets led to large uncertainties. A recent radiative muon capture measurement suggested a larger than 4σ discrepancy to the chiral prediction, leading to a flurry of theoretical activity.

Recent accomplishments and ongoing efforts

The MuCap experiment at the Paul Scherrer Institute, Switzerland, has developed a novel technique based on a time projection chamber filled with ultra-pure hydrogen as an active target. This allows for a first precise measurement of this process in a low-density gaseous target, where the ambiguities in the interpretation of earlier experiments are largely avoided. A first result reported in early 2007, determined the pseudoscalar coupling constant as $g_P = 7.0 \pm 1.1$, in agreement with the chiral predication. Further data are being collected, which will reduce the present uncertainty by more than a factor of 2. The new MuCap result represents decisive progress in a long-standing puzzle on a basic nucleon form factor and chiral symmetry test.

Future Opportunities

Once the question of g_P is settled, the developed precision technique enables the study of the axial current in the 2-nucleon system with the process $\mu + d \rightarrow n + n + \nu$. A one-percent measurement of $\mu + d$ capture would provide a benchmark result, 10 times more precise than all present experiments on weak processes in the 2N system. The results will determine the low-energy constant L_{1A}, which is common to these processes. In effect, it will help “calibrate the sun.” This program has strong ties to recent intense theoretical studies of the response of the two-nucleon system to electroweak probes in the framework of potential models and effective field theories, culminating in high-accuracy few-body calculations having estimated theoretical uncertainties below 1 percent. This progress has been fueled by astrophysics interests, in particular in the $\nu + d$ reactions observed by the SNO experiment and the solar *pp* fusion process. The EFT expansion demonstrated that exactly the same low-energy constant L_{1A}, which parameterizes contributions from short-range axial two-body currents, appears in all these fundamental reactions. Present experiments on $\mu+d$ capture are at the 10% precision level only, but MuCap has developed several key techniques that promise a tenfold reduction in experimental uncertainties. In order to eliminate interpretation uncertainties due to the presence of μd atoms in two hyperfine states, an optimized setup using a higher density TPC in being studied and a proposal is under preparation.

H. The new g-2 experiment

The idea behind E969 at BNL is to significantly increase the muons stored in the ring per AGS cycle and, at the same time, reduce the hadronic background that limited the E821 experiment fit start time. A new "backward decay" beam delivery concept has been developed by the New Muon g-2 Collaboration, which completely removes the pion contamination that enters the ring at injection. The hadronic flash will be absent. To increase the overall flux, four technical areas are being developed simultaneously. 1) The decay lattice quadrupole density will be increased by a factor of four. This results in a twofold transmission increase. 2) The superconducting inflector will be re-engineered with open-ends to remove muon scattering on the present, closed-end coils. This double the effective acceptance. 3) The kicker pulse is presently sub-optimal and can be improved significantly if the inductance of the system can be re-engineered. The kicker improvement greatly affects the storage efficiency, which is presently only a few percent. A better kick could double the stored muon fraction and largely remove the strong coherent betatron oscillation frequency present in the current data. 4) To maximize the pions entering the decay lattice, the upstream pion collection arc acceptance can be raised from 0.5% to roughly 3%. A 2nd-order achromat has been designed to control the chromatic aberrations inherent in such an increase. This improvement could greatly increase the overall flux, again by a factor of 2 or more. These four factors multiply and easily exceed the ×5 rate design improvement of the proposal. With increased rate, the detector system must be overhauled and a prototype W/SciFi calorimeter, which is much denser compared the current Pb/SciFi design, has been built and tested. However, R&D funds are urgently needed to allow proper engineering of the beam flux improvement plans and to develop blueprints for construction and for a full Technical Design Report with complete costing. Clearly, if the plans can be fully realized, the statistical improvement can greatly exceed the 0.2 ppm uncertainty promised in the proposal.

I. Electroweak Probes of the Strong Interaction

1. Parity-Violating Electron Scattering

As described earlier in the document, parity-violating electron scattering (PVES) continues to play an important role in low energy tests of the Standard Model. Over the past fifteen years, PVES has also emerged as a tool to probe novel aspects of hadron structure. Due to the different isospin weights of the neutral weak charges compared to the corresponding electromagnetic charges, measurements of judiciously chosen semi-leptonic weak neutral current amplitudes can probe the strange quark structure of the nucleon, the ground state neutron distribution of a heavy nucleus and test the limits of the quark-parton description of deep inelastic scattering.

Strange Quark Structure of the Nucleon

In elastic electron-nucleon scattering, the parity-violating asymmetry is sensitive to a linear combination of the nucleon electric and magnetic neutral weak form factors. Combined with measurements of the nucleon electromagnetic form factors using conventional electron-nucleon elastic scattering, these electroweak asymmetry measurements can be used to extract the strange electric and magnetic form factors. Over the past ten years, several precise measurements have been published from three laboratories: MIT-Bates, Mainz and Jefferson Laboratory (JLab). The world data from experiments A4, SAMPLE, HAPPEX and G0 out of these three laboratories are mutually consistent [107]. Tight constraints have been placed on the strange form factors, indicating that strange quarks and antiquarks contribute no more than a few percent to the nucleon charge and magnetic moment distributions. The final measurements on the strange form factors will be carried out over the next two to three years. These experimental measurements, especially when compared to various theoretical estimates, shed important new light on the role of the sea of quark-antiquark pairs within nucleons.

Ground State Neutron Distribution in a Heavy Nucleus

In the process of carrying out the above-mentioned physics program, asymmetries as small as 1 part per million (ppm) have been measured, with statistical and systematic errors approaching 10 parts per billion. This has enabled new experiments such as PREX at JLab, which aims to measure the neutron radius of ^{208}Pb to one percent by measuring the electroweak asymmetry in elastic electron scattering off ^{208}Pb. Parity violation provides a clean probe of the neutron density because the weak vector charge of the neutron is much larger than that of the proton. This measurement is important well beyond the subfield of PVES [108]. PREX will provide significant nuclear structure information and aid in the determination of the equation of state of neutron-rich matter. This in turn will help determine the density dependence of the symmetry energy. In addition, the measurement will constrain neutron radii that currently limit the interpretability of atomic parity violation experiments. Finally, PREX has important astrophysical implications for a variety of neutron-star properties, such as radii, crust thickness, composition, and cooling rate.

Parity-Violating Deep Inelastic Scattering with the 11 GeV JLab Upgrade

When Jefferson Laboratorys energy upgrade is complete, the continued improvement in PVES experimental techniques to make fractional measurements with sub-one percent accuracy presents a new opportunity to probe the quark structure of nucleons. The unprecedented luminosity with a 11 GeV beam makes precision studies of parity-violating deep inelastic scattering (PVDIS) possible. Combined with a new large solid-angle spectrometer based on a large volume and high-field solenoid, highly precise measurements can be made in PVDIS at very high Bjorken-x [104]. This would probe aspects of nucleon structure going beyond the conventional quark-parton model description of DIS. One can search for the onset of charge symmetry violation in the nucleon with unprecedented accuracy, as well as quantify the size of higher-twist effects in the weak neutral current amplitude. One can also make precision measurements of the ratio $d(x)/u(x)$ as x approaches 1. These topics are of long-standing interest in deep inelastic scattering studies.

While the abovementioned elastic and deep inelastic PVES programs have tremendous potential for new discoveries in nucleon and nuclear structure, a very important spinoff is the following: the nucleon is established as a clean and well-understood laboratory to probe the limits of the electroweak theory itself. The potential of such PVES measurements have been described earlier in the document. Here we only stress that such tests of physics at the TeV scale would not be possible without the detailed nucleon structure measurements that becomes available with the introduction of 11 GeV beams combined with a new large solid angle solenoidal spectrometer.

The theoretical interpretation of the PV DIS experiments requires progress on two fronts. The first involves understanding the level of isospin violation in parton distribution functions. The results of the NuTeV measurement of neutrino-nucleus DIS indicate a substantial deviation from Standard Model expectations, and the favored explanation is the presence of heretofore unknown isospin violation. The second entails a deeper understanding of higher twist effects. Recent results from parity conserving electroproduction carried out at Jefferson Lab suggest that higher twists effects are suppressed in the leading structure function moments at low momentum transfer, but that they could be substantial in higher moments. The dynamics behind these observations are not understood, and the possible implication for the PV DIS asymmetries remain to be elucidated. Thus, the PV DIS program at the 11 GeV beam provides both a new experimental opportunity and important new theoretical challenges.

2. Hadronic Parity Violation

Explaining the weak interactions of quarks as they are manifest in the decays in interactions of hadrons has been a long-standing quest for particle and nuclear physics. Although considerable experimental and theoretical effort has been devoted to this task, the hadronic weak interaction (HWI) remains enigmatic. Today, we understand the structure of the underlying interaction in the context of the Standard Model, but the realization of the HWI is complicated its interplay with the dynamics of the strong interaction in the nonperturbative domain. Of particular interest to nuclear physics is the strangeness conserving component of the HWI, as it generates weak interactions between nucleons. Probing the $\Delta S = 0$ HWI requires that one study the PV component of this interaction, as this is the only way to filter out the effects of the much larger strong NN interaction. As described below, recent theoretical advances, coupled with the opportunities for a new program of few-body PV measurements at the FNPB and other facilities, have now opened the way for achieving a substantially clearer understanding of the HWI in nuclear systems (for a recent review, see Ref. [86]).

The discovery of parity violation in nuclear beta decay occurred half a century ago, and soon thereafter Tanner initiated the first search for parity violation in the NN interaction. For the past five decades a series of increasingly precise experiments have been undertaken to find the basic characterization of the parity-violating NN interaction, but this interaction remains only partly understood. There are a number of reasons for this situation. One is that the feature that although the near threshold parity-conserving NN interaction can be completely characterized in terms of just two empirical constants—the spin-singlet and spin-triplet scattering lengths—five such low energy constants are required in order to completely describe the low energy parity-violating NN interaction. Also, the experiments are quite challenging in that the natural scale for such effects is $G_F m_\pi^2 \sim 10^{-7}$. A proper theoretical description is equally challenging in that both the strong and weak interactions are involved. It is important to realize that the study of hadronic parity violation is in essence, an exploration of the details of the nuclear strong force. The paradigm for the understanding of hadronic parity violation is based on assumption of the validity of the standard model for the electroweak interaction, and while the weak interaction is the essential part of hadronic PV effects, the ultimate goal is the understanding of the NN strong force at short distances.

Recent Theoretical Progress:

On the theoretical side, for the past twenty five years it has been customary to analyze the parity-violating nucleon-nucleon interaction in terms of a model-dependent single-meson-exchange model. In this picture the effects of the weak interaction are characterized in terms of the S-wave PV coupling to the charged pion as well as six PV nucleon-vector meson coupling constants. Each of these vector-meson interactions has both a convective and magnetic component and the relative strength of each is fixed by vector dominance of the strong interaction couplings. Recently a new effective field theory analysis has freed this analysis from its model-dependent roots. In this picture the relative strength of the convective and magnetic components is a free parameter. In addition the medium-range effects of two-pion exchange are included. The result is a rigorous framework within which one can confidently analyze experimental results. At the same time, significant advances in performing *ab initio* few-body computations have now made it possible to carry out highly precise computations of few-body PV observables using this EFT formulation without introducing the nuclear model-dependent uncertainties associated with many-body nuclear PV calculations. Finally, progress in lattice QCD has created realistic prospects for undertaking first principles computations of the low energy constants that characterize the PV NN interaction.

Experimental Progress:

On the experimental side, the essential opportunity concerns the measurement of parity violation in few nucleon systems. Our attention is drawn to such simple systems because, in the absence of nuclear structure effect, we are confident that the results of the above theoretical program will provide clean and reliable predictions. The experimental challenge lies in the fact that the size of the PV effect in such systems is un-enhanced by nuclear effects and is thus at the 10^{-7} mentioned previously. Measurements at this level not only require highly intense sources to provide sufficient statistical sensitivity but must also be carried out with extreme care to insure that systematic effects can be controlled with extreme sensitivity. The current opportunities for progress in the experimental study of result from the development of improved sources which can provide significant increases in intensity (see section on neutron sources) as well as in the refinement of experimental methods which can address the issue of systematic effects. In addition the operation of the fundamental neutron physics beamline at the SNS permits many such critical experiments to be accomplished.

Experimental and Theoretical Opportunities:

Given the foregoing advances, the path to a more complete explanation of the weak NN interaction is now clear. Theoretically, one can now utilize the best possible "exact" methods to characterize experimental observables in terms of the low energy constants of effective field theory. Doing so will allow one to extract these parameters from experimental observables much as one has done for the low energy constants that characterize the strong NN interaction for few-body systems or hadronic interactions using chiral perturbation theory. At the same time, there now exists an opportunity to generate a lattice program to evaluate these low energy constants in terms of fundamental QCD.

Needed Experimental Work:

The experimental program which should be pursed during the next five year period is involves several few-nucleon experiments. Some of these are ready for installation and data collection at current or so to be operational sources. Others are under development or await the results of these first round experiments for further refinement. The experiments that have been suggested are given below.

- Measurement of gamma-ray directional asymmetry with respect to the neutron spin in $\vec{n} + p \to d + \gamma$: This asymmetry isolates the long-range isovector component of the PV NN interaction. This project, which has completed a successful data run at LANSCE, has been approved as the initial experiment at the Fundamental Neutron Physics Beam at the SNS.

- Measurement of the PV neutron spin rotation in ^{4}He: This project is currently in progress at the NIST Cold Neutron Research Facility.

- Measurement of gamma-ray directional asymmetry with respect to neutron spin in $\vec{n} + d \to t + \gamma$: Feasibility studies for this project have been approved by the SNS FNPB.

- Measurement of the PV neutron spin rotation in Hydrogen: This is a straightforward, but operationally challenging extension of the ^{4}He spin rotation experiment and will probably await the results of the first-round experiments before proceeding

- Measurement of the longitudinal asymmetry of polarized neutrons on ^{3}He and of unpolarized neutrons on polarized ^{3}He: Detailed theoretical calculations are necessary to plan and interpret these experiments. In the limit that ^{3}He can be treated as a neutron the two measurement are identical. The difference in the two asymmetries will clarify the ability of nuclear few-body theory to interpret these related measurements.

- Measurement of the circular polarization of photons following n-p capture: This observable is particularly sensitive to the $\Delta I = 2$ part of the PV NN interaction. The experiment is probably not feasible with facilities that currently exist or that will be available shortly. A "through tube" or a dedicated beam at future high-power spallation source together with improvements in analyzers may bring the experiment within reach. An alternative approach is threshold photo disintegration of the deuteron with circularly-polarized neutrons. Higher intensities than are presently available at free-electron-laser photon sources would be required.

With the successful completion of a program including the above theoretical program AND as many of the experiments as are feasible a clear picture of the role of the weak interaction where leptons are not involved be understood.

J. Sub-gravitational Tests of the "Two Standard Models"

Many intriguing theoretical speculations, often motivated by string or M-theory, predict fundamentally new phenomena not contained either in the SU(3) × SU(2) × U(1) standard model of particle physics or in Einstein's standard model of gravity. Mechanical experiments that detect exceedingly weak forces can probe regimes that lie beyond the reach of conventional accelerator and non-accelerator experiments. Because these tests employ test bodies containing roughly 10^{23} particles they can attain remarkable sensitivity to exotic macroscopic forces with ranges from 10 μm to infinity. The exquisite sensitivity of the results gives such experiments real discovery potential (recall that modern string theories tend to predict many essentially massless bosons). Most of these experiments now employ torsion balance technology.

Current experiments focus on:

- Weak Equivalence Principle tests. These are sensitive probes for any new vector or scalar interactions with ranges greater than 1 cm.

- Tests of the gravitational inverse square law. The current emphasis is on very short ranges (less than 100 μm) or on very high precision at longer ranges. The short-range experiments, which use torsion balances, probe possible large extra dimensions, as well as new Yukawa forces from the exchange of proposed exotic bosons. The most precise long-range tests use laser-ranging to the moon. The extreme precision here (1 mm uncertainty in the shape of the moon's orbit) provides the best tests of the Strong Equivalence Principle (the EP applied to gravitational energy itself), possible time-or-space variation of Newton's constant (current limits are $\dot{G}/G \leq 10^{-12}$), very large extra dimensions that would allow gravitons to "leak away", etc.

- Searches for novel cosmic effects using torsion pendulums containing 10^{23} polarized electrons. These look for extremely feeble effects that would cause an electron to precess very slowly about a direction fixed in inertial space; torsion balances (in distinction to atomic clocks) give one sensitivity to all three orthogonal directions. Here one looks for new manifestations of a preferred-frame defined by the Universe itself. One class of effects occur in the Standard Model Extension of Bluhm and Kostelecky [87] which assumes that the early universe spontaneously generated vector and axial vector fields that have since been inflated to enormous extents; producing very feeble Lorentz (and also CPT-violating) effects. Current experimental sensitivity is about 10^4 times below the Planck scale expectation of $m_e^2/M_{\rm Planck}$. These tests also explore the con-commutative geometry scenario that has been suggested by string theorists. Current limits on the minimum observable path area is several hundred Grand Unification lengths-squared corresponding to several times 10^{13} GeV^2. This is well beyond the reach of any accelerator experiment.

K. Opportunities in Neutrino Astrophysics

1. Solar Luminosity in Neutrinos and Photons

Over 99% of neutrinos from the sun have energies below 2 MeV, where no spectroscopic data are currently available. Measurement of the full spectrum of these neutrinos would provide a model-independent determination of the current rate of nuclear energy generation in the solar core, allowing a fundamental comparison with the current photospheric luminosity. A measurement of the solar luminosity in neutrinos to achieve new science goals implies three basic requisites: 1) Data on the complete low energy spectrum (not just the *pp* neutrinos) i.e. the individual fluxes of the *pp*, Be, *pep* neutrinos and at least a reasonably definite one of CNO neutrinos; 2) precision in the flux measurements and 3) the background involved in the measurement is directly measured, not only estimated. Such data directly yield the solar luminosity in neutrinos if neutrinos are massless. This neutrino luminosity can be directly compared with the photon luminosity. The comparison probes whether, 1) nuclear reactions are the only source of energy in the sun and 2) energy generation in the sun remains in quasi steady state in a time scale of the order of the difference between the emission time of light and that of neutrinos of $\sim 10^5$ years for energy generated at the same time as neutrinos. We know however, that neutrinos have non-zero mass and they oscillate in or on the way from the sun. Thus, to get the true solar neutrino luminosity, we must correct the measured neutrino fluxes using the best neutrino model and parameters to work back to the original fluxes in order to carry out the above neutrino-photon luminosity comparison. This process is largely independent of solar models since the parameters used to calculate the energy generated in the emission of a specific neutrino flux is unambiguously fixed by nuclear physics. The derivation of neutrino physics from measured fluxes has always been subject to the dichotomy of neutrino physics and solar models. The comparison of luminosities avoids this dichotomy and places all conclusions on an experimental basis for the first time. This comparison is therefore a powerful independent calibration of the sun's energy that tests not only the astrophysics of the sun (past, present and future) but also of the new neutrino physics. A measure of the expected progress in luminosity comparison via a precision measurement of the complete low energy solar neutrino spectrum is indicated by the large uncertainties encountered in using presently measured solar neutrino data. The ratio $L(\nu)(\text{inferred})/L(h\nu) = 1.4^{+0.2}_{-0.3}$; 1σ) by one estimate [124] and 1.12 ± 0.2 (1σ) by another [125], instead of 1.00. The only way to improve this comparison is via spectroscopic data of the individual fluxes to $\sim 3-4\%$ i.e., of each of the *pp*, Be, *pep* and a modest precision of the CNO fluxes. The importance of individual fluxes is illustrated by the fact that part of the apparent luminosity imbalance inferred at present can be traced to the complete lack of information on the CNO flux. This flux is now subject to major new theoretical uncertainty because of the controversy on the opacities due to optical measurements indicating a 30-40% decrease in concentrations of light elements such as C and O.

2. Solar Dynamics, the CNO Flux

Current dynamic solar models include motion and activity inside the sun that may transform part of the produced nuclear energy into kinetic and magnetic energy, which are not accounted for in the Standard Solar Model (SSM) (which assumes perfect and prompt transport of nuclear energy to the photosphere). Neither are they part of the luminosity balance as described above. The precise determination of current nuclear energy generation via the neutrino luminosity thus also tests the emerging dynamic solar models. Measuring the time variability of the *pp* neutrino flux would also put some constraint on the variability of the radiative zone in time. We already know from helioseismology that the convective zone evolves with time (rotation profile, meridianal circulation, magnetic fields), but it is more difficult to include motions (which clearly exist) of the radiative zone. The *pp* neutrinos are a good indicator because they are sensitive to practically 60% of the mass of the sun and their flux is not dominated by the solar temperature profile. Therefore, the *pp* neutrinos have a real sensitivity to density variations in latitude and are a good indicator on the dynamics of the Sun. In contrast, even a determination with relatively modest precision (20%) of the previously unmeasured CNO neutrino flux would be very interesting for understanding the metallicity of the solar core and the migration of CNO elements within the sun over time. While the CNO contribution to nuclear energy generation is small (a few percent of the total luminosity), these elements play a very important role in the solar opacity. We know that they migrate from the surface to the center of the sun over time, but the abundance of CNO isotopes in the stellar core is quite uncertain. A measurement of the CNO neutrino flux would provide crucial information on the abundance of these elements in the stellar core.

3. Detecting the diffuse supernova neutrino background

It is now established that detection of the diffuse supernova neutrino background is within reach of Super-Kamiokande, if its background rejection capabilities are improved by adding dissolved gadolinium to tag neutrons[111]. This would be the second-ever detection of supernova neutrinos, and also the first detection of neutrinos from beyond 1 Mpc. Since recent theoretical predictions for this flux are at or above the level presently limited by Super-Kamiokande, an important goal is to interpret future results in terms of measurements of supernova neutrino emission parameters, and therefore on the physics of the proto-neutron star.

Very recent astrophysical data have greatly reduced the uncertainty on the cosmic supernova rate and its evolution, and favor large rates[112]. The dominant uncertainty on the predicted diffuse supernova neutrino background flux is now the neutrino emission per supernova, which is what is needed to test the nuclear physics aspects of supernovae[110].

4. Detecting a Milky Way supernova

While Milky Way supernovae are rare, occurring only a few times per century, the detection of the neutrino signal would revolutionize all aspects of supernova studies. It would be a tragedy to miss this opportunity, and thus the only option is to develop and maintain as much capability as possible, perhaps for decades. The longer-term goal is to build much larger detectors, such that a Milky Way supernova would be measured with sufficiently high statistics to precisely constrain models. Such detectors, likely at the Mton scale, will also be able to detect neutrinos from supernovae in nearby galaxies, with a rate as high as ~ 1 neutrino per year, collected from nearby supernovae, which have a rate as high as ~ 1 per year[113].

5. Optimizing supernova neutrino detection capabilities

The diffuse supernova neutrino background flux is faint, and Milky Way supernovae are rare, and accordingly, there is a strong benefit to enhancing the neutrino detection capabilities of all available detectors, most of which are primarily intended for other purposes. Research and development work is needed to develop and implement detector modifications and supernova triggers. A coordinated network is needed to quickly recognize a real supernova by its neutrino signatures alone. Since the termination of the Sudbury Neutrino Observatory, a glaring deficiency is a detector with good sensitivity to electron neutrinos, which are particularly important for testing supernova models; developing a new technique is an important goal.

6. Solving the supernova explosion problem

A long-term and central nuclear physics problem is to solve the question of how a supernova explodes, with the ultimate goal being to develop a standard model of all aspects of the neutrino signal, nucleosynthetic yields, neutron star properties, cosmic rays, etc. Besides urgently needing new neutrino data to select among the possibilities, this problem requires a coordinated attack using computational and theoretical techniques.

7. Probing the origin of the elements

What is the origin of the elements? This is a very broad question, requiring understanding the birth, quiescent burning, and death of stars. Of special interest is the origin of the heavy elements formed in the rapid neutron capture process, probably in core-collapse supernovae, though this remains to be confirmed. It is also important to explain the recent nucleosynthesis products in the Milky Way, probing the last million years of evolution, and revealed by MeV gamma rays from positron annihilations, ^{26}Al decay, and ^{60}Fe decay. The cumulative elemental abundances of the universe also need to be synthesized with the history of star formation and the nucleosynthetic yields per star.

8. Utilizing new high-energy probes of supernovae

How does the debris from a supernova explosion interact with the interstellar medium, sharing its nucleosynthetic yields and accelerating cosmic rays? How can this be tested by observations of high-energy neutrinos, gamma rays, and cosmic rays? Do the observed Milky Way TeV gamma ray sources produce their gamma rays through the hadronic mechanism (via pion decays, and also producing comparable fluxes of neutrinos), or via the leptonic mechanism (via inverse Compton scattering of energetic electrons)?

Cherenkov observatories like HESS and MAGIC are making good measurements of gamma-ray spectra from supernovae; over the next decade neutrino observatories like IceCube and the European km^3 effort will make similar studies with neutrinos. The neutrinos will clarify the role of hadronic acceleration in supernova remnants, and thus shed light on how heavy elements are accelerated and spread throughout the galaxy

9. Maximizing the interdisciplinary impact of nuclear physics

Progress in neutrino astrophysics and cosmology crucially depends on theory to synthesize results from nuclear physics, particle physics, astrophysics, and cosmology. In addition, because of the difficulties of neutrino detection, there is a clear benefit to theorists working closely with experimentalists to optimize the physics reach of detectors. Approximately 20 nuclear theorists are supported by U.S. funding agencies to work in these areas. Given the impact of this work, the rapid pace of progress, and the appeal of this work to students, this investment should be strengthened. The techniques and insights of nuclear physics could and should have a large impact on synthesizing and interpreting new astrophysical data.

10. Testing cosmology

How many neutrino flavors are there? The number of active flavors is precisely determined from the width of the Z boson, but is it the same as the number deduced from successful big-bang nucleosynthesis of the light elements and the relativistic energy density deduced from cosmic microwave background measurements? Are the persistent discrepancies in the light-element yields a signature of new physics acting in the early universe? How robust is the cosmological limit on the sum of the neutrino masses, and how does it compare with laboratory limits? If both are significantly tightened, then signals of nonzero mass are expected, and potentially the differences in the measurements can reveal new physics.

11. Are there ultra-high energy neutrinos from astrophysical sources?

The HESS, MAGIC, and VERITAS telescopes have found numerous Milky Way TeV gamma-ray sources, many associated with known supernova remnants. For hadronic sources, where the gamma rays arise from neutral pion decays, comparable fluxes of neutrinos are expected from charged pion decays. IceCube will have the sensitivity to test if the gamma rays are of hadronic or leptonic origin, and hence the interaction of supernova explosions with their environments and the acceleration of cosmic rays. Similarly, at ultra high energies, around 10^{18} eV, there are new experiments being deployed that have the sensitivity to detect the predicted neutrino fluxes.

L. Neutrino Interactions

Understanding of the interactions of neutrinos with nuclei will be essential for achieving many of the physics goals described in this document. For example, core collapse physics and supernova nucleosynthesis depend critically on the interaction of the neutrino flux with collapsed stellar material, and many detection channels of supernova neutrinos involve neutrino-nucleus interactions. The neutrino oscillation physics program also requires understanding of neutrino-nucleus cross-sections, and the change in final-state configurations and energy due to rescattering within the nucleus. We still lack much knowledge of neutrino-nucleus interactions in both low and high energy regimes; theoretical calculations generally have quite large uncertainties, and in many cases experimental measurements are sparse or non-existent. A rich experimental program of measurements is called for in order to get the most from our future neutrino program. Furthermore, neutrino-nucleus cross-section measurements will provide information on nuclear and hadronic structure. The intense flux of neutrinos being produced at the Spallation Neutron Source at Oak Ridge National Laboratory now provides a timely, cost-effective opportunity to conduct a program of precise neutrino-nucleus cross section measurements that would address these issues.

As most neutrino experiments are performed with nuclear targets, the interpretation of an experiment often depends on the quality of the modeling of the nuclear response. This is an important challenge for nuclear theory and phenomenology, one that requires increased collaboration between the theory community and experimental analysis teams. The field needs more reliable techniques for the near-threshold, quasi-elastic, resonance, and deep inelastic regions and the transitions between these regions. It also needs theory-inspired phenomenologies, useful for experimentalists, that faithfully represent the nuclear structure physics and kinematics of the underlying models. Recently developed approaches such as superscaling represent an important step toward this goal.

The following sections will highlight particular needs for cross-section measurements over a range of energies.

1. Supernova Neutrinos

For the few tens of seconds after a massive star collapses, dense stellar matter is awash in neutrinos with energies in the few tens of MeV range. These neutrinos are intimately involved in the resulting supernova explosion, and likely power it; they also drive supernova nucleosynthesis processes. If we are to understand the mechanism of core collapse supernovae and their role in Galactic chemical evolution, we must understand how these neutrinos interact with matter. Furthermore, a unique means of learning about supernova physics (and neutrinos themselves) will be to detect the giant burst of neutrinos from a nearby core collapse that arrives at Earth: since many detection channels involve interactions of neutrinos on nuclei, precise understanding of these interactions will be important in interpretation of the observations. The only relatively well-measured neutrino-nucleus cross-sections in this energy regime to date are those from LSND and KARMEN on ^{12}C.

The following section will briefly describe topics for which new measurements would have significant impact.

- **Core collapse supernova dynamics:** Supernova simulations are notoriously troubled by frequent failure to create explosions following core collapse. It is believed that the huge flux of neutrinos plays a significant role in powering the explosion; however the particular mechanisms by which the neutrinos couple energy to the collapsed stellar matter depend on the specifics of neutrino-matter interactions. Electron/neutrino capture on heavy nuclei during the collapse is particularly important for understanding the dynamics during this phase. Cross-sections for ν_e capture on many nuclei up to $A \sim 100$ are needed for accurate simulations. Coherent elastic neutral current neutrino-nucleus scattering also affects neutrino opacities and core collapse dynamics.

- **Supernova nucleosynthesis:** Supernova nucleosynthesis occurs via several processes in different parts of the star, and neutrinos play important roles in all of them. In the "α-rich freezeout", which occurs during explosive nucleosynthesis induced by passage of the shock wave, the presence of neutrinos can affect the resulting elemental and isotopic composition of the iron-rich ejecta. In "neutrino nucleosynthesis", neutrino interactions break apart nuclei, leading to creation of rare isotopes. A "neutrino-driven wind" also affects the r-process, which generates half of the elements heavier than iron. For understanding of all of these processes, information about neutral and charged current neutrino interactions with nuclei will be extremely valuable.

- **Supernova neutrino detection:** A core collapse supernova in our own Galaxy will generate a huge burst of interactions in neutrino detectors around the world. The detection of the supernova flux will be invaluable for understanding of the properties of neutrinos themselves, as well as being a window into the deepest layers of the collapsed star. In water and scintillator-based detectors (Super-K, Amanda/IceCube, LVD, KamLAND, Borexino), the bulk of the observed interactions will be in the inverse beta decay channel, which is well understood; however, there will be additional interactions on carbon and oxygen, which are less well understood. Furthermore, several proposed future supernova neutrino detectors will rely on charged and neutral current interactions on heavy nuclei; lead is a particularly promising target. Coherent elastic scattering is another potential detection channel in low threshold detectors. Neutral current interaction measurements are particularly interesting since they are the only way to access the muon and tau components that will represent a large fraction of the supernova neutrino flux.

The highest priority nuclei to measure for supernova neutrino physics are O, C, Fe, and Pb.

The supernova neutrino energy regime is suitable for exploring some other physics. For example, neutrino-nucleus cross-sections will allow testing of nuclear structure models; key selected targets can help tune theoretical models which will be relevant for a wide range of nuclei. Another example is neutrino-nucleus coherent elastic scattering, for which the cross-section is cleanly predicted by the Standard Model and a measured deviation from prediction could be a signature of new physics.

M. Interdisciplinary Opportunities

In addition to the foregoing opportunities that fall squarely in the purview of nuclear science, members of the community are involved in research efforts that lie at the interface with other subfields and for which the primary capital equipment support has been provided by the corresponding agency offices (*e.g.*, high energy physics). The participation of nuclear scientists in these interdisciplinary efforts provides the field with additional opportunities to make significant contributions to research having major discovery potential. We highlight four such activities below.

1. Reactor Neutrino Oscillation Studies

The recent APS neutrino study recommended an expeditiously deployed multi-detector reactor experiment with sensitivity to electron antineutrino disappearance down to $\sin^2 2\theta_{13} \sim 0.01$, an order of magnitude below present limits. Indeed, knowing the precise value of θ_{13} is important in several respects. If it is not too small, i.e. close to the current upper limit of $\sin^2 2\theta_{13} \sim 0.1$, then the neutrino mass matrix does not have to have any special symmetry features. However, if θ_{13} is much smaller than the current limit, special symmetries of the neutrino mass matrix will be required [119]. In addition, the CP-violating phase in the neutrino mixing matrix multiplies the term $\sin^2 2\theta_{13}$, i.e. CP-violation in the neutrino sector requires a non-zero value of θ_{13}. There is a clear intellectual link between measuring θ_{13}, possible leptogenesis in the Early Universe, and precision EDM measurements.

Some of previous neutrino oscillation measurements were interdisciplinary efforts. KamLAND was designed as a joint project between nuclear physics and high energy physics. Daya Bay follows in this tradition, and offers the field a cost-effective opportunity to participate in exciting high-priority neutrino physics while partnering with DOE-HEP, China, and other countries. Although the US capital construction funds will be provided by DOE-HEP, there are several US nuclear physics groups playing key roles in this project. It is essential that the NP funding agencies support these groups to insure the success of this very important international project.

2. Charged-Lepton Flavor Violation

Charged-lepton flavor violation (CLFV), lepton universality, and lepton properties in general have acquired added significance in the light of developments in the neutrino sector and will remain centrally relevant in the future. CLFV processes occur in nearly all scenarios for physics beyond the SM. Further, SM predictions of CLFV based on neutrino mixing are far below experimental accessibility so that any observation of CLFV will be an unambiguous signal of physics beyond the SM. The Mu2e experiment will exploit neutrinoless, coherent flavor conversion in the field of a nucleus that will be three times more sensitive than MEG ("mu to e-gamma") for photon mediated processes and three orders of magnitude more sensitive for most other types of non-SM contributions. The measurement of $R_{\mu e} = \Gamma(\mu A \to eA)/\Gamma(\mu A \to \nu A)$ to a precision of $\sim 10^{-16}$ will need $\sim 4 \times 10^{20}$ protons producing 10^{18} muons, which can be obtained using 10 to 20% of the beam at FNAL for 2 4 years of running. If supersymmetry is observed at the LHC, this measurement will be essential to sort out lepton favor violation.

Studies of CLFV have a natural overlap with the program of $0\nu\beta\beta$ in nuclear physics. In particular, the possibility exists that the exchange of heavy Majorana particles, such as the neutralinos or gluinos of supersymmetry, can generate a neutrinoless decay signal with rate comparable to what one expects for the exchange of a light Majorana neutrino. If one wishes to exploit $0\nu\beta\beta$ to determine the absolute scale of neutrino mass, then one must know that such heavy particle exchange effects are either absent or sub-dominant. As discussed in Ref. [76], searches for CLFV can provide a useful diagnostic for the presence of heavy particle exchange effects. Thus, it is important to provide research support to nuclear physicists who may participate in a CLFV search.

3. Dark Matter Searches

It is now well known that non-luminous cold dark matter (CDM) makes up roughly 25 % of the energy density of the universe. The composition of the CDM remains unknown, although a number of theoretical scenarios have been widely discussed. Two appealing possibilities are weakly interacting massive particles (WIMPs), such as the neutralinos in supersymmetric models, and axions. The existence of the latter are a natural consequence of explaining the vanishingly small value of the QCD $|\bar{\theta}|$ parameter in terms of a spontaneously broken Peccei Quinn symmetry. Extensive experimental effort has been invested in direct and indirect searches for WIMPs and axions (for a brief review, see a companion white paper on dark matter in nuclear physics[77]). An additional interesting candidate is a sterile neutrino with mass ranging from $\sim 1 \rightarrow 100$ keV and that mix with the ordinary active neutrinos at the level of one part in $\sim 10^9 \rightarrow 10^{12}$. Sterile neutrino CDM can be probed by looking for photons produced in neutrino decay using X-ran astronomy.

The search for CDM has strong overlap with key elements of the nuclear physics mission. In supersymmetric models, for example, the relic abundance of the lightest supersymmetric particle that is the CDM candidate is closely coupled to the viability of electroweak baryogenesis[78]. In the Minimal Supersymmetric Standard Model (MSSM), for example, the values of the supersymmetric mass parameters needed to generate the observed baryon asymmetry can be in the same region as needed to obtain the CDM relic abundance (depending on other cosmological parameters). Moreover, the search for high energy neutrinos produced in the earth or the sun can provide a powerful probe of WIMP dark matter. Such neutrinos would be produced by WIMPs that become gravitationally trapped in the sun and annihilate to produce $\nu\bar{\nu}$ pairs. Looking for these neutrinos is a natural extension of nuclear physics studies of low energy solar neutrinos. Axion searches are a similarly natural endeavor for nuclear physics, since elucidating the properties of QCD and its manifestations are a key component of the mission of the field.

Apart from the scientific overlap that dark matter studies have with nuclear physics, cryogenic detection methods developed by nuclear scientists for low background studies such as for $0\nu\beta\beta$ and solar ν detectors have a natural and important application to cryogenic CDM detectors. Thus, nuclear scientists are currently involved in the development of large cryogenic detectors that could be used in CDM searches, such as the CLEAN, DEAP, and XENON and indirect searches for WIMP annihilation in the Sun and Earth.

Determining the content of CDM would constitute one of the major discoveries of the next decade. Participating in this effort (or these searches) represents a unique opportunity for nuclear science, and one to which our field brings a number of significant strengths.

4. Neutron-Antineutron Oscillations

In an experiment complementary to the EDM, the search for neutron-antineutron oscillations directly provides information on the baryon asymmetry of the universe. Theoretical supersymmetric models that include baryon number violation have recently predicted values for the $n\bar{n}$ transition time that are only one to two orders of magnitude away from the present experimental limits. An improved experiment could either observe $n\bar{n}$ oscillations or significantly restrict the parameter space for particular neutrino mass models. These searches test physics at the energy scale of $\sim 10^5$ GeV. Support for experimental R&D for such an $n\bar{n}$ oscillations search would be needed to establish the feasibility of an experiment with improved sensitivity.

V. BROADER IMPACTS

Nuclear physicists involved in neutrino and fundamental symmetry efforts are squarely at the intersection of the science fields that include nuclear, particle and astrophysics (and cosmology). We pursue answers to scientific questions that address the development of the universe from its earliest moments; we seek to explore the very core physics that leads to the present universe as we know it. The understanding and development of the current Standard Model is one of the most significant intellectual achievements in the physical sciences, with many leading contributions being made by nuclear physicists. Our current program continues to challenge the Standard Model as well as help refine it. Indeed, physicists know that the Standard Model is incomplete. That we are "here" is the simplest proof—the baryon asymmetry of the universe (BAU) alone demands that new physics must exist beyond this Standard Model. Not only do our efforts explore such limits, but we also will help establish what will become the New Standard Model once the physics responsible for the BAU and other deficiencies is uncovered. This exciting venture is naturally very broad, quite interdisciplinary and has contributors and proponents from many subfields of physics.

Nuclear physicists can be very proud of the leading roles played in the establishment of neutrino oscillations and the determination of the key mixing parameters of the neutrino matrix. As elaborated in subsequent paragraphs, results from the SNO and KAMLAND experiments have had tremendous and well-deserved exposure in the larger science community. Likewise, the muon g-2 experiment and the E158 Møller experiment have searched with great sensitivity for the missing physics of short distances and high mass scales in a way that current particle accelerators cannot yet achieve. Indeed, the muon anomaly now indicates a deviation from the theoretical prediction at the 3.4 standard deviation level, which is arguably the strongest hint of new physics that must be understood.

The success and impact of the U.S. neutrino physics program since the last long range plan has been striking and has received widespread recognition in both the scientific literature and the popular press. In 2001, Science Magazine identified SNO's solution of the Solar Neutrino Mystery as one of their 10 Breakthroughs of the year in Science. The next year, 2002, the general topic of "Neutrino Insights" was identified by Science Magazine as the first runner-up Breakthrough of the Year in Science, with both the SNO and KamLAND experiments highlighted. More recently, Science Magazine featured IceCube on it's front cover, leading off a special issue on particle astrophysics. The issue included several review articles involving nuclear physics

Another measure of impact is citations. In January-Feburary 2003, ScienceWatch®, a research service that tracks important papers in all of science, noted in its identification of "Hot Papers in Physics" that half of the top 10 cited papers were on neutrinos, and four of those were on solar neutrinos. In their November-December 2003 summary, ScienceWatch pointed out that SNO held the top three places in the Physics Top Ten, and SNO then continued this run into 2004 with the three papers remaining in the top 10. According to ScienceWatch KamLAND had the second most cited paper in all of science in 2002-2003. As a final example, the July-August 2004 ScienceWatch list of "Hot Papers in Physics" noted that four of the top 10 cited papers were on solar neutrinos with two from SNO, and a paper from both KamLAND, and SuperK.

The SPIRES-HEP database that tracks citations in particle physics observed the increased interest and impact of low-energy neutrino physics. In their top 50 papers cited in 2003, six were for low-energy neutrino physics, including three papers by SNO, and papers by SuperKamiokande on solar neutrinos, by KamLAND, and on the Homestake Cl experiment. In 2004 there were 7 low-energy solar neutrino papers in the top 100 cited papers, and in 2005 there were six papers in the top 50 and 9 in the top 100. According to SPIRES, in terms of total citations, where they catogorize papers with 500 or more citations as "renowned" and those with between 250-499 as "famous" SNO has two papers with over 1000 citations, a 2001 Phys. Rev. Lett. [16] with 1312 and a 2002 Phys. Rev. Lett. [17] with 1336. KamLAND's 2004 Phys. Rev. Lett. [22] has 1256 citations, and their 2004 Phys. Rev. Lett. [23] has 409. SuperKamiokande has 831 citations for their 2001 Phys. Rev. Lett.[6] and 525 citations for their 2002 Phys. Lett. [7], both on their solar neutrino results. The gallium experiments have also continued to have significant impact, with GALLEX's 1999 Phys. Lett. [13] having 906 citations and the SAGE 1999 Phys. Rev. C [11] having 544. The 1998 Chlorine Homestake Astrophys. J. paper [2] now has 1229 citations.

While the fields of neutrino physics and fundamental symmetries lie at the intersection of several subfields of physics and astronomy, nuclear physics plays a crucial role. It is not possible to carry out and interpret most of the experiments discussed in this White Paper without knowledge and input of nuclear physics. Nuclear physics, in particular, dominates the field of solar neutrinos which resulted in the "top three" discoveries of the past decade and was awarded a recent Nobel Prize. These top three discoveries that nuclear physics steered were i) First observation of solar neutrinos with the Homestake experiment, ii) Resolution of the solar neutrino problem and the observation of solar neutrino flavor change at SNO; and iii) First observation of reactor antineutrino disappearance at KamLAND. We are now in a position to measure and understand the complete solar neutrino spectrum, with significant implications for solar and stellar astrophysics, including the theory of main-sequence stars. The solar neutrino program builds on existing investments and modest scale new detectors. These detectors are multi-purpose and have "guaranteed signals." Furthermore recent advances in technology for solar neutrino experiments open new opportunities. Another great opportunity for doing low energy solar neutrino experiments could be provided by the ongoing DUSEL process.

The neutrino mass scale is crucial for comparisons to cosmological limits on the mass energy density of the relic neutrinos from the early universe. Recently claimed limits are rapidly approaching the scale at which a discovery could be made, and we will require similarly sensitive laboratory measurements for comparison. The existence of additional neutrino flavors could radically change the physics of these and other systems.

Several results in the field of Fundamental Symmetries have also proven to be extremely important in testing the Standard Model, with broad impact beyond the respective subfields. Fundamental symmetry tests at low energies can provide information about an energy regime presently inaccessible to the highest energy accelerators. The result on the muon anomalous magnetic moment, tantalizingly different from the SM prediction, continues to receive considerable theoretical attention; in fact, the project publications have been cited more than 1300 times [116]. The 2001 paper was the most cited experimental paper in HEP that year. The results have been featured prominently in the media (New York Times, USA-Today, and other papers) and in the popular physics journals. *Muons: Particles of the Moment* was a feature article in the March 2004 edition of Physics World [117].

The E158 result on parity violation in Møller scattering was another result that had significant impact on the indirect search for clues to physics at the highest energy scales. Apart from its unique constraints on new physics beyond the reach of existing collider measurements, the E158 project was recognized for its numerous technical innovations in the broader physics community. The first E158 result, which constituted the first observation of parity-violation in the interaction between two electrons, as well as the final precision result, were listed as one of the American Institute of Physics's Top New Stories in 2004 and 2005. The experiment was featured in articles in Nature (May 2005) and Physics Today (September 2005).

Experiments in this subfield have also benefited the National Interest in other ways as illustrated by this unique example. Part of the MuCap experiment was supported by the U.S. Civilian Research and Development Foundation to develop an advanced gas purification system and electronics, combining the Russian expertise with Western technology. In addition to scientific merit, this very competitive award emphasizes broader benefits for technology, infrastructure, civilian research for Russian former defense scientists and the mutual benefit of USA Russian cooperation. Former Russian weapons scientists played a major role in this fundamental science project. A (rare) renewal of the project led to the development of an isotopic purity system making, for the first time, essentially fully deuterium-depleted hydrogen.

Finally, it should also be pointed out that the field of neutrino physics and fundamental symmetries continuously attracts graduate students and plays a significant role in the training of young nuclear physicists. A large number of recent faculty appointments at prominent universities highlight the visibility of the field in the physics community.

VI. FACILITIES

Experimental work in Neutrinos and Fundamental Symmetries often involve sensitive and challenging techniques and depend on specialized facilities in much the same way that research in QCD and Nuclear Structure does, although the facilities are very different. Many of the past successes in our subfield, as well as some of our future proposed new initiatives, take advantage of highly leveraged existing installations. The traditional resource has been accelerator facilities with unique characteristics for carry out specific challenging measurements, such as BNL, LANL, JLab, SLAC and PSI. In our roadmap for the future, we will continue to take advantage of these installations, such as continued availability of proton beams at the AGS, muon beams at PSI and the upgraded 12 GeV electron beam at JLab.

In addition, the future physics potential of our field is greatly enhanced by the opportunities presented by two dedicated new facilities. These facilities, on which we elaborate in the following, would make possible not just a single experiment but accommodate a number of experimental programs.

A. DUSEL

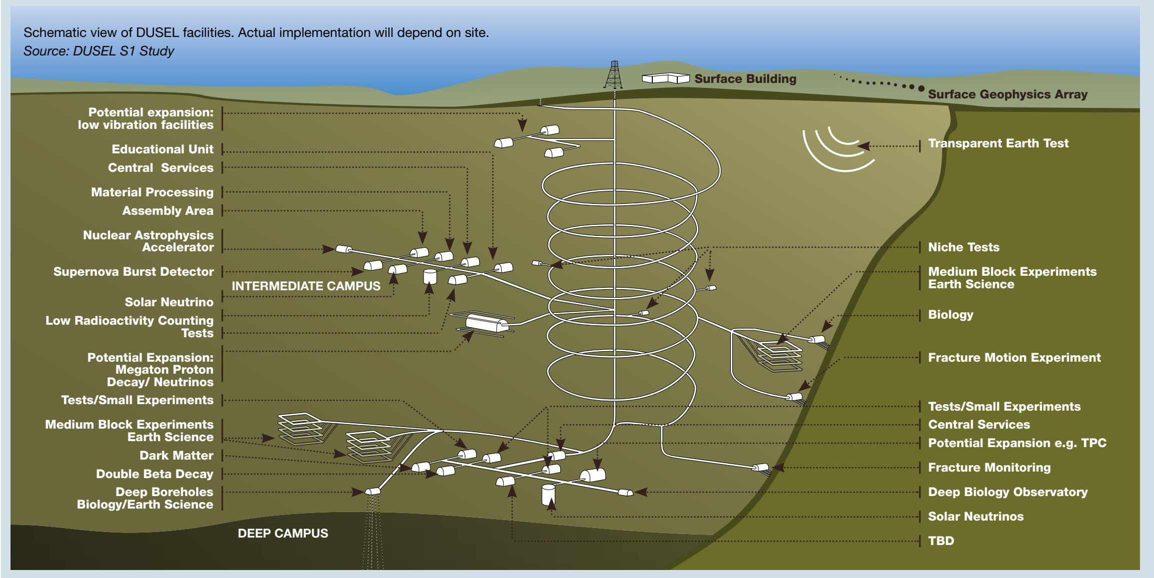
The highest priority of the neutrino community is to support the National Science Foundation's Deep Underground Science and Engineering Laboratory (DUSEL) Initiative to construct the world's deepest and most comprehensive, dedicated, multipurpose underground laboratory. The DUSEL Initiative will fund facility infrastructure and, importantly, an Initial Suite of Experiments. The DUSEL Initiative positions the nuclear physics community to assume leadership in the fields of neutrinoless double beta decay, low energy solar neutrinos, geoneutrino measurements, and precision determination of nucleosynthesis cross sections for nuclear astrophysics. In addition the DUSEL initiative will provide exciting opportunities for nuclear physicists to develop key infrastructure such as state-of-the-art low background radioactive assay facilities, ultrapure material production facilities, and to participate in dark matter searches, next generation supernovae monitors, and long-baseline neutrino experiments.

The specific arrangement of laboratory space underground would depend on the site, but a generic possibility is illustrated in Fig. 7.

The NSF has solicited proposals for construction of the Laboratory, and is in the process of reviewing those proposals. It is expected that the total project cost may be in the vicinity of \$500M, of which approximately half would be for the facility infrastructure, and half for the initial suite of experiments.

B. Fundamental Neutron and Neutrino Physics at the SNS

When the Condensed Matter community reached consensus on the construction of the Spallation Neutron Source, it created an opportunity for the development of the Fundamen-



Schematic view of DUSEL facilities. Actual implementation will depend on site.
Source: DUSEL S1 Study

FIG. 7: A possible arrangement that meets the scientific objectives of a Deep Underground Science and Engineering Laboratory. This figure is taken from the DUSEL S1 Study [132].

tal Neutron Physics Beamline (FPNB) by which some longstanding goals in Fundamental Symmetries research could at last be achieved. The intense pulsed cold beams from SNS can be used for a number of basic measurements of neutron beta-decay parameters and parity violation, and a cold beam makes possible a search for a neutron electric dipole moment with sensitivity some 100 times better than present limits. The FPNB has been approved and funded, and construction is nearing completion. Total project cost is approximately \$10M, not including the experiments.

The SNS also creates a unique opportunity for the nuclear physics community to address the need for data on neutrino cross sections. Only a handful of neutrino-nucleus cross sections are known by direct experimental measurement, but such cross sections play a crucial role in the modeling of supernova nucleosynthesis and in the interpretation of many fundamental experiments on neutrino properties. The intense flux of ν_μ, $\overline{\nu}_\mu$, and ν_e from the stopped pion source at SNS exceeds the most intense previously available (at Los Alamos) by about a factor of 10. SNS management has agreed to make space available for a facility for measuring neutrino cross sections at the beam stop. The facility, 'NuSNS', is proposed to cost approximately \$10M.

In addition, the SNS presents a unique and unparalled opportunity to explore neutrino oscillations due to its low energy, well-understood neutrino spectra, and monoenergetic muon-neutrinos from pion decay. If MiniBooNE confirms the LSND neutrino oscillation signal, then a follow-up experiment, OscSNS, would have the capability of proving that sterile neutrinos exist and searching for additional, new physics beyond the Standard Model. The estimated cost of OscSNS is $\lesssim$ \$15M

VII. RESOURCES

A. Current Support Levels

The Neutrinos and Fundamental Symmetries program has delivered important advances in nuclear physics, but has remained a very small part of the total investment of DOE and NSF in nuclear physics. A measure of that ratio (for neutrino physics) may be gained by examining Table I, in which the US FY2006 funding for the worldwide neutrino program is summarized. This Table also contains the world effort in neutrino physics listed by project name, and the suite of major new experiments and projects that are proposed for the next advances in the field.

The amounts shown are for operating or R&D, and are in some cases rough estimates. To our knowledge, the only capital expenditures by DOE or NSF on neutrino projects at this time (FY2006) are for the Super-Kamiokande repair and for IceCube.

Support for neutrino physics in FY06 amounted to 2% of the total DOE nuclear physics budget, and about 10% of the NSF budget that can be identified with nuclear physics.

B. Future Needs of the Field

Although there are a number of truly exciting science opportunities and challenges involving neutrinos, the low-energy U.S. neutrino community is facing a grave crisis in terms of funding support from the U.S. Nuclear Physics agencies. The SNO experiment has completed its measurements and is now being supported for decommissioning and for the completion of the analysis of the data collected during the third phase of the experiment. There is continued NP support for the existing BOREXINO, KamLAND, and MiniBooNE experiments. One major new project, KATRIN, is confirmed to be supported.[2] DOE operating is being used to support the US groups that are collaborating on the KATRIN experiment, and the request for construction support ($3 M) has been tentatively approved. There is a DOE mission need statement (CD-0) for a neutrinoless double beta decay project, and DOE has allowed existing neutrino groups to redirect some operating for R&D development, but currently no project is being supported to move forward to the next step (CD-1) required for construction of a new Major Item of Equipment project.

Thus, the recommendations laid out in 2004 in the Joint DNP/DPF/DAP/DPB Joint Study on the future of Neutrino Physics have not been implemented and the proposed schedules for developing new experiments have fallen seriously behind. Meanwhile the international neutrino community continues to move ahead on a number of these fronts with funding support. Given the rich opportunities in neutrino physics, a solution to this

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[2] The situation for U.S. funding support from High Energy Physics is somewhat better, with the current SuperK and MINOS experiments being supported, and funds being provided for the new projects NOvA [55], T2K, Daya Bay [56], and EXO.

TABLE I: US FY2006 support in $k for projects in neutrino physics worldwide. The support is for operations or R&D, with the exception of IceCube, which is under construction, and Super-Kamiokande, which was refurbished. Entries that are blank are unknown.

Project	DOE NP	DOE HEP	NSF	Other
Solar				
Borexino	0	0	1460	
KamLAND	1100		0	
LENS	0	0	0	270
SAGE	0	0	0	
SNO (a)	3800	280	0	650
SNO+	0	0	0	
Accelerator, Reactor				
CERN-LNGS (b)	0	0	0	
MiniBooNE	1100	1750	693	
MINERvA	0	1000	100	
MINOS	0	7000	648	
NOvA	0	4000	0	
NuFactory	0	3400	300	
NuSNS	0	0	0	100
Proton Driver	0	8000	0	
Super-K	0	1700	193	
T2K	0	2100	0	
UNO	0	0	0	
Daya Bay	0	800	0	
Double Chooz	0	0	235	
Single Beta Decay				
KATRIN	400	0	0	
MANU/MARE	0	0	0	
NEXTEX	0	0	150	250
Double Beta Decay				
CANDLES (b)	0	0	0	
COBRA	0	0	0	0
CUORE			320	
EXO	100	1500	0	
GERDA (b)	0	0	0	
Majorana	700	0	0	1100
MOON (b)	0	0	0	
NEMO-II/III	0	26	0	50
Astrophysics, Facilities, Theory				
AMANDA/IceCube	0		53252	
ANITA	0			
DUSEL	0	0		
Theory	17 FTE		3 FTE	

[a] Final year of data taking [b] No US participation

serious problem must be found or the U.S. will concede major involvement in this entire research area.

In the Fundamental Symmetries program, there are significant investments being made by DOE Nuclear Physics. The FNPB at SNS is under construction, and support for R&D on the neutron EDM experiment as well as other neutron measurements is being provided. The EDM experiment has passed Critical Decision CD-1. Project baseline funding occurs at CD-2. A significant part of the FS program is carried out at JLAB, and those experiments receive support as a part of the JLAB research budget. The muon g-2 experiment being carried out at Brookhaven is supported by both NSF and DOE. It is clear, however, that the imperatives toward this kind of research stemming from the breakdown of the Minimal Standard Model cannot be met without a substantial infusion of resources.

The program of research that makes up the proposed Initiative on the New Standard Model calls for equipment funding. An approximate profile for this funding is shown in Fig. 8.

VIII. PRINCIPAL RECOMMENDATIONS

The discovery of neutrino oscillations have provided the first direct evidence for physics beyond the Standard Model of strong and electroweak interactions, and measuring properties of neutrinos, including neutrino mass, mixing angles, and charge conjugation properties, is essential for elucidating the structure of the "new Standard Model". The observation of neutrinoless double beta decay and/or the permanent electric dipole moment of the neutron, neutral atoms, or nuclei would constitute major discoveries having significant implications for both the symmetries of the new Standard Model and cosmology. These measurements, together with precise measurements of Standard Model processes such as weak decays, parity-violating asymmetries, and the muon anomalous magnetic moment, provide a powerful window on the new Standard Model with a physics reach that complements and in some cases exceeds that achievable at present and future high-energy colliders. By pursuing these studies, nuclear physics will realize a historic opportunity to contribute substantially to the development of the new Standard Model.

Fully realizing our historic opportunities will require investing in a major new nuclear physics Initiative in neutrinos and fundamental symmetries. The success of this initiative depends critically on the construction of Deep Underground Science and Engineering Laboratory that will provide a domestic home base where searches for neutrinoless double β-decay and precise studies of the low energy solar neutrino spectrum can be carried out. At the same time, this initiative will require continuing and new investments in studies of fundamental symmetries and neutrinos at other major nuclear physics facilities and robust support for university-based research groups.

Therefore:

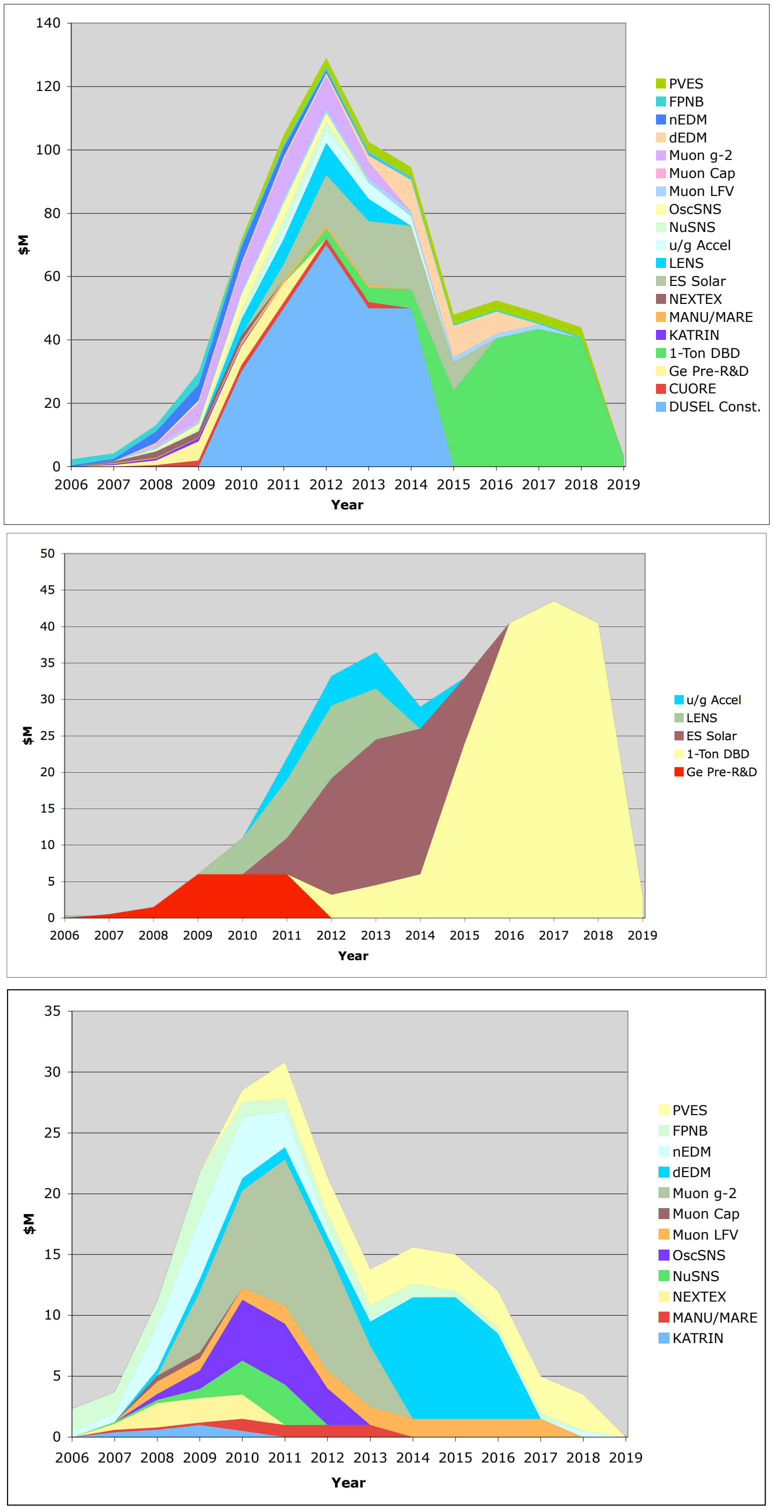

FIG. 8: (Top) Estimated project funding for Neutrinos and Fundamental Symmetries; (Middle) Projects that are candidates for DUSEL; (Bottom) Non-DUSEL candidates.

- **We strongly recommend investment in a "New Standard Model Initiative", anchored by the construction of a Deep Underground Science and Engineering Laboratory, and including experimental searches for neutrinoless double beta-decay and permanent electric dipole moments together with a targeted program of precision measurements of Standard Model processes and neutrino properties.**

This recommendation reflects the priorities for Neutrinos and Fundamental Symmetries that are summarized below and that provide a roadmap for the Initiative. The priorities are as follows:

The basic properties of the neutrino decisively affect a wide range of physical phenomena, such as the formation of nuclei in the cosmos, and possibly the very dominance of matter over antimatter. Neutrino mass, now known to be non-zero, may have shaped the large-scale structure of the universe. Determinations of the mass, whether lepton number is violated, and the sizes of the mixing angles, are major goals for physics. Success in many aspects of this program requires the ultra-low-background environment that would be provided by a deep underground, dedicated laboratory. The experiments in low-energy neutrino physics and nuclear astrophysics requiring this specialized environment include neutrinoless double beta decay, solar neutrinos, and measurement of stellar-energy nuclear cross sections with an accelerator.

1. We recommend construction of a Deep Underground Science and Engineering Laboratory, and its complement of experiments in neutrinoless double beta decay, solar neutrinos, and nucleosynthesis. In the shorter term, we recommend immediate support for modest scale experiments in neutrinoless double beta decay, antineutrino oscillations at nuclear reactors, and measurements of the absolute neutrino mass in nuclear beta decay.

New searches for permanent electric dipole moments (EDMs) have great potential for the discovery of CP-violation beyond that of the Standard Model, which may be of great importance in explaining the origin of the baryonic matter-antimatter asymmetry of the universe. It is essential to carry out EDM searches with a variety of systems that have complementary dependences on possible sources of CP-violation, including both the strong sector of the Standard Model as well as Standard Model extensions. As one of the simplest neutral hadrons that could possess an EDM, the neutron provides a unique probe of both strong and new electroweak CP-violation.

2. We strongly recommend capital investment in, and support for, the nEDM experiment at the FNPB. We also recommend support for searches for rare-isotope EDMs and R&D toward a storage-ring based deuteron EDM measurement.

High-precision low-energy measurements complement, and in some cases exceed, the physics reach of high-energy collider searches for new physics beyond the Standard Model. The recent successful completion of precision electroweak measurements in nuclear physics, *together with significant advances in experimental techniques and theoretical predictions for low-energy electroweak observables, have created an opportunity for a new generation of high-impact precision electroweak studies during the next decade.*

3. We strongly recommend a targeted program of precision electroweak studies at facilities such as FNPB, JLab, LANSCE, NIST, and BNL. Present and future opportunities having unique sensitivities to new physics include measurements of the muon anomaly, neutron decay parameters, and polarized electron scattering asymmetries.

Neutrinos are a unique probe of the inner mechanism of supernovae and other astrophysical objects and also determine the elements produced therein. A standard supernova neutrino model can now be envisaged that would provide a reliable framework for calculations of supernova nucleosynthesis. Properties of stellar core collapse neutrinos, such as timing, energetics and flavor content will be predicted, based on neutrino scattering in dense matter, neutrino oscillation physics, the dense matter equation of state, neutrino transport and magneto-hydrodynamic inputs. To complete this program, experimental inputs to theoretical models, such as neutrino cross section measurements at accelerator facilities, are required. Direct observation of core collapse supernova neutrinos, a detection of the diffuse supernova neutrino background, and detection of gamma ray burst neutrinos require readiness of existing and future neutrino detectors. This will provide invaluable data with which prediction will be compared.

4. We recommend a unified experimental and theoretical program in nuclear physics to construct a standard supernova neutrino model to understand how elements are produced in these explosions, and to develop a secure foundation from which to investigate other cataclysmic astrophysical events, such as gamma-ray bursts.

Nuclear physicists make vital contributions to studies that involve large capital investments from other subfields. Their involvement provides a highly leveraged opportunity for U.S. nuclear science to participate in experimental efforts having both strong ties to the core mission of the field and major discovery potential with broad impact beyond the traditional horizons of nuclear science.

5. We recommend support for nuclear physicists involved in interdisciplinary efforts such as measurements of the neutrino mixing angle θ_{13} through reactor and long-baseline experiments, direct and indirect searches for dark matter and sensitive tests of charged lepton flavor violation.

The small community of nuclear theorists supported to work in this subfield have played an essential role in the interpretation of experiments, the development of future research directions, and the articulation of their impact in the broader physics community. Despite the success of their work, however, a number of key theoretical challenges remain to be addressed. In many cases, significant contributions originate from our young scholars. The impact of new experimental efforts can be realized only if these theoretical challenges are successfully addressed through additional support for students and post-doctoral fellows. The present level of support for theoretical efforts in fundamental symmetries and neutrinos constitutes roughly 2% of the total DOE nuclear theory allocation.

6. We strongly recommend new investments in the next generation of nuclear theorists who are critical to the future of neutrino and fundamental symmetry studies, and targeted support for initiatives to solve the key scientific problems identified in this White Paper.

IX. CONCLUSIONS

The last decade has wrought a dramatic change in the fabric of physics. Fields never very far apart – nuclear physics, particle physics, cosmology, and astrophysics – have converged to the conclusion that nature contains clearly identifiable features that are not accommodated in the Standard Model that has served physics so well until now. Gravity has never been accommodated, of course, but no striking conflict with the Standard Model was thereby produced. There was always the possibility that the Standard Model was simply a subset of a larger model that included gravity, and that it was complete and accurate within its jurisdiction. The presence in the universe of dark matter and dark energy, now almost beyond question, says that 95% of the universe is made of things not present in the Standard Model. Although those observations do not directly contradict Standard Model predictions, they drastically narrow its jurisdiction and – like gravity – point strongly to the need to embed it within a larger framework.

It is now inescapable that the observations involving the remaining 5% of the universe made up of Standard Model particles present direct contradictions with various aspects of the theory. Given the lower bound on the mass of the Higgs boson and the strength of CP violation as contained in the CKM matrix, the Standard Model predicts a far smaller excess of matter over antimatter than is observed. Similarly, the observation of neutrino oscillations and the implications that neutrinos have non-vanishing masses require definite changes in the electroweak sector of the Standard Model as invented by Glashow, Weinberg, and Salam. It may be that these changes involving neutrinos or new sources of CP violation that could be uncovered in EDM searches will allow us to explain why the visible matter that makes up the stars, earth, and human life itself exists.

Mapping out the features of the new Standard Model can be a central quest for nuclear science and we have an exciting opportunity to help write the next chapter in the development of our understanding of the forces of nature at the most fundamental level. Indeed, the exciting nuclear physics discoveries in neutrino physics and the tantalizing results of precise measurements of Standard Model properties – such as the muon anomalous magnetic moment and the low energy weak mixing angle – have placed our field in a strong position for this task. In this White Paper, we have set forth the next steps in our pursuit of a more complete understanding of the fundamental interactions in nature.

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