DUSEL Theory White Paper

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I. EXECUTIVE SUMMARY

The scientific case for a Deep Underground Science and Engineering Laboratory [DUSEL] located at the Homestake mine in Lead, South Dakota is exceptional. The site of this future laboratory already claims a discovery for the detection of solar neutrinos, leading to a Nobel Prize for Ray Davis. Moreover this work provided the first step to our present understanding of solar neutrino oscillations and a chink in the armor of the Standard Model of particle physics. We now know, from several experiments located in deep underground experimental laboratories around the world, that neutrinos have mass and even more importantly this mass appears to fit into the framework of theories which unify all the known forces of nature, i.e. the strong, weak, electromagnetic and gravitational.

Similarly, DUSEL can forge forward in the discovery of new realms of nature, housing *six fundamental experiments* that will test the frontiers of our knowledge:

1. **Searching for nucleon decay** (the decay of protons and neutrons predicted by grand unified theories of nature).

2. **Searching for neutrino oscillations and CP violation** by detecting neutrinos produced at a neutrino source (possibly located at Brookhaven National Laboratory and/or Fermi National Laboratory).

3. **Searching for astrophysical neutrinos** originating from the sun, from cosmic rays hitting the upper atmosphere or from other astrophysical sources, such a supernovae.

4. **Searching for dark matter particles** (the type of matter which does not interact electromagnetically, yet provides 24% of the mass of the Universe).

5. **Looking for the rare process known as neutrino-less double beta decay** which is predicted by most theories of neutrino mass and allows two neutrons in a nucleus to spontaneously change into two protons and two electrons.

6. **Searching for the rare process of neutron- anti-neutron oscillations**, which would establish violation of baryon number symmetry.

A large megaton water Cherenkov detector for neutrinos and nucleon decay, located in DUSEL and roughly 20 times the size of current detectors, can perform the first three of these experiments. The last 3 can utilize the unique environment afforded by DUSEL to perform the most sensitive tests to date. Any one of these experiments can greatly increase our knowledge of nature.

The Deep Underground Science and Engineering Laboratory (DUSEL), with a Large Megaton Size Detector, is desperately needed to address a set of fundamental issues in particle and astrophysics.

- Evidence for proton decay would confirm and test grand unified theories of the four known forces. It would open a unique window onto physics at the very highest energy scales. However it is important to recognize that any large proton decay detector is a multi-purpose discovery observatory. It is also a powerful neutrino observatory.

- Neutrino oscillations involving the transformation of one species of neutrino into another has been discovered, but there is a whole world of New Physics lying buried in the neutrinos. In particular, it pertains to the question of the violation of a certain symmetry called CP, which combines the symmetry C, that interchanges matter and anti-matter, with the symmetry P that reflects spatial directions. Learning about the violation of this combined symmetry CP can shed light on the origin of an excess of matter over anti-matter in the early Universe, which is crucial to the origin of life and thus to our very existence. In addition we need to know the ordering of the masses of the three neutrinos and their mixings accurately. A large size detector with linkage to a long baseline neutrino facility would enable us to probe into these issues of great fundamental importance.

- Finally, observing in detail solar neutrinos, or detecting the neutrinos from a supernova explosion or other point sources of cosmic neutrinos will greatly enhance our knowledge of both neutrinos and the physics of the exotic engines that produce these neutrinos.

To summarize, the discovery potential of such a detector is high. It could of course be built in modules , each of about 140 kilotons, and at least five such modules would be needed to achieve the desired goals. Because of its unique multi-purpose value and its physics significance, such a Large Size Detector at DUSEL, coupled to a long baseline neutrino beam (which could be provided for example by Fermilab), would be one of the greatest assets to the U.S. and the world as a whole.

It would greatly complement the physics that may be learned from the forthcoming Large Hadron Collider and would thereby enhance the U.S. High Energy Physics efforts at the very highest energy frontiers.

Any discovery of dark matter, whether underground or at a collider or best yet, both, will be associated with new physics beyond the standard model. In addition, the discovery of dark matter in an underground detector can provide a unique window on the distribution of the dominant form of matter in our galaxy and in the Universe.

The searches for neutrino-less double beta decay or neutron anti-neutron ($n\bar{n}$) oscillations have long been identified as sensitive probes of physics beyond the standard model. The observation of neutrinoless double beta decay and/or $n\bar{n}$ oscillations will provide unequivocal evidence that these neutral particles are their own anti-particles. Either discovery would have major implications for our understanding of nature.

The theory community is excited by the prospect of DUSEL, since this would create a U.S. center for studies of proton decay, neutrino oscillations and astrophysics, dark matter, and the very nature of the neutrino and the neutron and other possible forefront experiments probing the properties of nature. In the history of particle physics, laboratories have always triggered very fruitful interactions among theorists and between theorists and experimentalists. Theory workshops could be hosted at DUSEL, as well as yearly executive summaries of theoretical progress for experimentalists and of experimental progress for theorists.

Underground laboratories are now operating at the Gran Sasso mine in Italy, at Kamioka, Japan and the Sudbury Neutrino Observatory in Canada, and DUSEL-like facilities are being discussed in Japan, Europe, and India. Now is the time for the U.S. to take the lead in this exciting area of physics, since major discoveries, which can revolutionize our understanding of nature, are expected. Finally, in the forthcoming era of large direct detection collaborations, it will be strategic for the US scientific community to have a laboratory like DUSEL in the US, preventing the risk of a drain of human resources outside the country, with dangerous consequences for both our experimental and theoretical physics community. Also, the health of our economy depends on the education of our future scientists and engineers and the technology they can develop. A national facility such as DUSEL can be a guiding light for our future scientists and engineers.

II. SEARCH FOR PROTON DECAY AT A MEGATON OBSERVATORY

A. Executive Summary

The search for proton decay at a Large Size Detector can dramatically shed light on the fundamental aspects of the laws of nature. In particular:

- Improved studies of proton decay would enable us to probe nature at the highest energy scale of order 10^{16} GeV (which is a trillion times larger than the energy that would be available at the LHC), or equivalently at truly short distances of order 10^{-30} cm—something that would not be possible by any other means.

- The discovery of proton decay would have profound significance for unification ideas. The idea of grand unification proposes, on aesthetic grounds, to unify the basic constituents of nucleons (so-called quarks) and the non-nuclear particles, like electrons and neutrinos, as aspects of one kind of matter. Simultaneously it proposes a unity of the three basic forces— the strong, weak and electromagnetic. This idea predicts, contrary to the belief commonly held till the 1970s, that the proton must decay, albeit with a long lifetime exceeding 10^{30} years. While proton decay has yet to be seen, the grand unification idea has turned out to be spectacularly successful as regards its other predictions. These include in particular the phenomena of "coupling unification," amounting to an equality of the strengths of the three forces at very high energies, which has been verified to hold at an energy scale of 10^{16} GeV by the precision measurements carried out at the CERN Laboratory in Geneva in the 1990s. Furthermore, a class of grand unified models naturally predict that the heaviest of the three neutrinos should have a mass in the range of a hundredth to one electron-Volt, and the next-to-heaviest an order of magnitude lighter, the two being quantum-mechanical mixtures of what one calls nu-mu and nu-tau. This too is in full accord with the discovery of neutrino oscillation at the Super-Kamiokande Laboratory in Japan in 1998. In this sense, proton decay now remains as *THE MISSING PIECE* of grand unification.

  With the discoveries of both coupling unification, at the scale of 10^{16} GeV, and of neutrino oscillation, one can in fact argue, within a class of well-motivated ideas on grand unification, that proton decay should occur at accessible rates, with a lifetime of about 10^{35} years, within a factor of ten either way, for protons decaying into positron plus neutral pion, and a lifetime of less than a few $\times 10^{34}$ years [in theories with 3 space dimensions] for proton decaying into anti-neutrino + a positively charged K-meson. Moreover, it is a very exciting

fact that whether the former or latter decay mode dominates depends on the number of space dimensions. With 3 spatial dimensions the latter mode typically dominates, while in higher dimensions, the former modes can give lifetimes of order 10^{34} to 10^{35} years. Hence, these predictions lie at a striking distance—within a factor of about 5 to 10—above the current lower bound set by the Super-Kamiokande Laboratory. Thus, unless the successes listed above are mere coincidence, there is a strong likelihood that proton decay would be discovered, IF one can improve the current sensitivity (of Super-Kamiokande) by a factor of 5 to 10. This is why an improved search for proton decay, possible only with a Large Size Detector, is now most pressing. Proton decay, if found, would no doubt constitute a landmark discovery for mankind.

B. Proton Decay

Protons, neutrons and electrons are the fundamental building blocks of all stable matter. They are the basic ingredients for chemistry and biology. Neutrons are stable when found deep inside the nucleus of an atom. However free neutrons are known to decay. When a neutron decays (there one minute, gone the next) it is replaced by a proton, an electron and the mysterious particle, called a neutrino. Neutrons and protons are held tightly inside the nucleus via strong nuclear forces. Neutrons decay via the weak force. The neutron lives on average about 1000 seconds when free. This number is called the lifetime of the neutron and is given in terms of the relation $\tau_{neutron} \sim \frac{M_W^4}{\Delta m_N^5}$, where $\Delta m_N \approx m_n - m_p$ is the neutron - proton mass difference and M_W is the W boson's mass. The weak interactions are so weak because the W boson is much heavier than the nucleon (proton or neutron) and $\frac{M_W}{\Delta m_N} \approx 30,000$.

But is the proton stable? If it could decay, then what would it decay into? What would its lifetime be? When a neutron decays, it does so preserving a quantity called *baryon number* or *baryon charge*. Both protons and neutrons interact via strong nuclear forces and both are *baryons* with *baryon charge* $B = +1$. The anti-particles of the proton and neutron exist and they have *baryon charge* $B = -1$. When a proton (with $B = +1$) and an anti-proton (with $B = -1$) meet they annihilate releasing their considerable mass energy (*recall* $E = mc^2$) into other forms of energy with total $B = 0$. On the other hand, when a neutron ($B = +1$) decays, it decays into a proton (also with $B = +1$) and an electron and anti-neutrino (both with $B = 0$). The sum of the baryon charges of the initial and final states agree! Hence baryon charge is conserved. Protons are the lightest baryons. All observed processes appear to conserve baryon charge. For a proton

to decay it must conserve energy and electric charge. Electric charge and energy conservation laws are associated with long range forces, i.e. electromagnetic and gravitational, respectively. Baryon charge conservation, on the other hand, is NOT associated with any long range force. In fact, not only is it not understood why baryon charge should be conserved, most theories beyond the standard model do NOT conserve baryon charge.

If baryon charge conservation were violated then protons might decay, for example via the processes $p \rightarrow e^+ \pi^0$ or $p \rightarrow e^+ \gamma$, where e^+ is the anti-electron (or positron), π^0 is the neutral pi meson and γ is a photon. If protons were to decay rapidly, then all chemistry and life as we know it would come to an abrupt end. The fact that life exists at all implies $\tau_p > 10^{18}$ years, since each and every proton or neutron (eg. $n \rightarrow \bar{\nu} + \pi^0$) in our body can decay and release its mass in deadly radiation. Similar to the weak decay of the neutron, the proton lifetime is given by an expression of the form $\tau_p \sim M^4/m_p^5$ where M is a new scale of nature. The existence of life then implies $M > 10^{12} \, m_p$. In units appropriate to accelerator energies, the proton mass, $m_p \approx 10^9$ electron $-$ Volt$/c^2 = 1$ GeV$/c^2$ (Giga-eV$/c^2$). For comparison, the Fermilab Tevatron has a maximum energy of 1.8×10^{12} eV $= 1.8$ TeV (Tera-eV), while the Large Hadron Collider, soon to turn on at CERN in Geneva, Switzerland, will have an energy of 14 TeV. The bottom-line is that the search for proton decay explores physics at the highest energies, much higher than is reachable in any accelerator experiment. Moreover, as we discuss later, an observation of proton decay would forever change our understanding of nature, with ramifications for understanding why there is more matter, than anti-matter in the Universe, and the proposed grand unification of the four known forces of nature.

C. Matter- anti-Matter asymmetry of the Universe

We are made of baryons, NOT anti-baryons. But why is this so? The answer: baryon charge must be violated. Without baryon charge violation (assuming equal numbers of baryons and anti-baryons initially) it is easy to show that most of the baryons and anti-baryons in the Universe would annihilate and we would be left with too few baryons. Why assume equal numbers? Otherwise, we would require the baryon to anti-baryon asymmetry to be set by (some) hand. This said, it has been shown that baryon charge violating processes can be used to derive the observed matter-anti-matter asymmetry.

D.   Probing high energies with proton decay at a Large Size Detector

Any new physics *beyond the standard model* predicts new energy scales with new particles and forces. In many cases, baryon charge violating interactions are also expected. One well-motivated idea for new physics beyond the standard model is known as *supersymmetric grand unified theory*. Grand unification describes the unity of the strong, weak and electromagnetic interactions, as well as the the unity of quarks and leptons. Grand unified theories are also naturally incorporated into *superstring theory* resulting in the unification of strong, weak, electromagnetic *and gravitational* interactions; the penultimate unification!

We expect the grand unification of the strong nuclear force with the weak and electromagnetic forces at a scale $M_G \sim 10^{16}$ GeV. Grand unification of strong, weak and electromagnetic interactions requires unification not only of these forces but it also requires the unification of quarks and leptons. Meaning that quarks and leptons are indistinguishable at their most fundamental level. This is not just the hope of enthusiastic physicists, it is in fact suggested by data. The LEP experiment at CERN made the most precise measurements of the coupling strengths of the strong, weak and electromagnetic interactions. Using this data it was shown that the these three couplings can unify at a grand unification scale M_G, provided that there is a doubling of the particles in nature, i.e. provided that this doubling is described by *supersymmetric GUTs*. Thus IF grand unification is real, then these new supersymmetric partners of ordinary matter should be observable at the Large Hadron Collider soon to take data at CERN!! Thus the LHC may open another unique window onto energy scales of order the Planck scale (where gravity becomes strong).

Independent of grand unification the new scale M of order 10^{14} GeV can be used to explain the observation of neutrino oscillations. Electron and muon neutrinos (there are three families of leptons, called electron, muon and tau, each with its own neutrino species) are produced in the upper atmosphere when cosmic ray protons hit air molecules. It has been demonstrated by experiments at Super-Kamiokande in Japan that muon neutrinos change into tau neutrinos on their way to the surface of the earth. This experimental result is explained by neutrino mass. However neutrinos are nevertheless some 100 million times lighter than the electron. This amazing fact is explained most naturally by the so-called See-Saw mechanism. The light neutrino is *light* as a consequence of a very *heavy* new energy scale $M \sim 10^{10}$ to 10^{14} GeV, with $m_{\text{neutrino}} \sim (m_{\text{lepton}})^2 / M$. Finally neutrino mass and neutrino oscillations are a natural component of grand unified theories.

Proton decay with accessible rates is a crucial prediction of the idea of grand unification (see
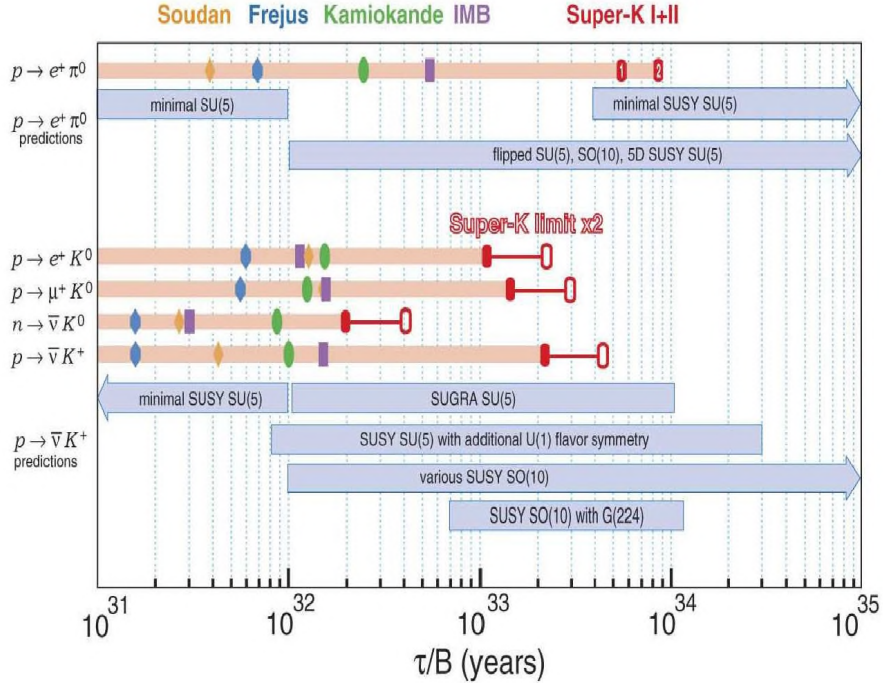
FIG. 1: Super-Kamiokande bounds on some prominent proton and neutron decay channels with predictions from some well-motivated theories. Courtesy of E. Kearns, NNN07 talk.

Fig. 1). What is the expected lifetime of the proton? The answer to this question depends on whether the theory is realized in four space-time dimensions or in higher dimensions, as might be expected in string theory, such as in 5, 6 or 10 dimensions with sizes not much larger than the Planck length. In four dimensions, very conservatively, most models predict an upper bound on the proton lifetime $\tau(p \rightarrow K^+ \bar{\nu}) \leq$ few $\times 10^{34}$ yrs., while for the other dominant decay mode, $\tau(p \rightarrow e^+ \pi^0) \sim \mathcal{O}(10^{36}$ years). On the other hand, for grand unified theories in higher dimensions $\tau(p \rightarrow e^+ \pi^0)$ can be as low as 10^{33} years.

Perhaps grand unification is wrong. Perhaps the LHC will explore large extra dimensions with strong gravitational interactions as low in energy as $M \sim 10$ TeV. Such theories are strongly constrained by the non-observation of proton decay. They must naturally have, or impose, a symmetry strongly suppressing baryon charge violation. For example, if space-time is 6 dimensional (*with two large extra dimensions*), then it was shown that the proton decays via the process $p \rightarrow e^- \pi^+ \pi^+ \nu \nu$. This decay is highly suppressed and leads to a lifetime on the order of 10^{35} years. However, in more general large extra dimension models an almost exact baryon charge symmetry must be imposed or else they are already excluded by the non-observation of proton decay.

Finally, strong gravitational processes are expected to induce proton decay at a scale $M \sim M_{Pl} = 10^{19}$ GeV, where M_{Pl} is the scale at which Newtonian gravity becomes strong. This would give $\tau_p > 10^{46}$ years, (assuming nature is NOT supersymmetric) which would be unobservable by all proposed proton decay experiments. But this dour prediction is an unlikely scenario. In addition, if supersymmetry is discovered at the LHC, then even if there is no grand unification, we still expect proton decay at observable rates just from strong gravitational induced processes.

To summarize, *every grand unified theory predicts that the proton will decay.* Moreover, we may need to describe nature (with or without grand unification) in more than three space dimensions or eventually with superstring theory. Indeed, in every single case it is expected that the proton will decay. The dominant decay mode for the proton (and neutron) is model dependent. Yet the lifetime is typically less than 10^{36} years, *and in many cases it is much lower.*

E.   History of proton decay experiments

The dedicated search for proton decay began in the early 80s. The best bounds now come from the Frejus experiment, France; Soudan 2 and IMB, USA, and Kamiokande (and Super-Kamiokande), Japan. These experiments have not seen evidence for proton decay. Thus they set limits on the proton lifetime. The best limit from Super-Kamiokande (preliminary) is $\tau(p \rightarrow e^+\pi^0) > 8.4 \times 10^{33}$ yrs or Super-Kamiokande I for the mode $\tau(p \rightarrow K^+\bar{\nu}) > 2.3 \times 10^{33}$ yrs.

Nevertheless, notwithstanding the lack of proton decay events, the IMB experiment (located near Cleveland, OH) and Kamiokande made a stupendous, serendipitous discovery of super-Nova neutrinos in 1987; confirming the theory of super-nova collapse!! In addition, Super-Kamiokande has been key to understanding solar and atmospheric neutrino oscillations. Hence an experimental program started initially to see protons decay has been instrumental in our understanding of neutrino properties, as well as our understanding of astrophysics; *two major successes.*

F.   Future proton decay detectors

A large size water Cherenkov detector is proposed for the DUSEL site. It is a megaton detector which can be built in 140 kiloton modules. With 5 such modules, the proton decay measurements can be sensitive to a lifetime of order 10^{35} years (see Fig.s 2 and 3); good enough to test most models for new physics beyond the standard model of particle physics. It is important to note that any proton decay detector is also a neutrino observatory. All such detectors are designed with a
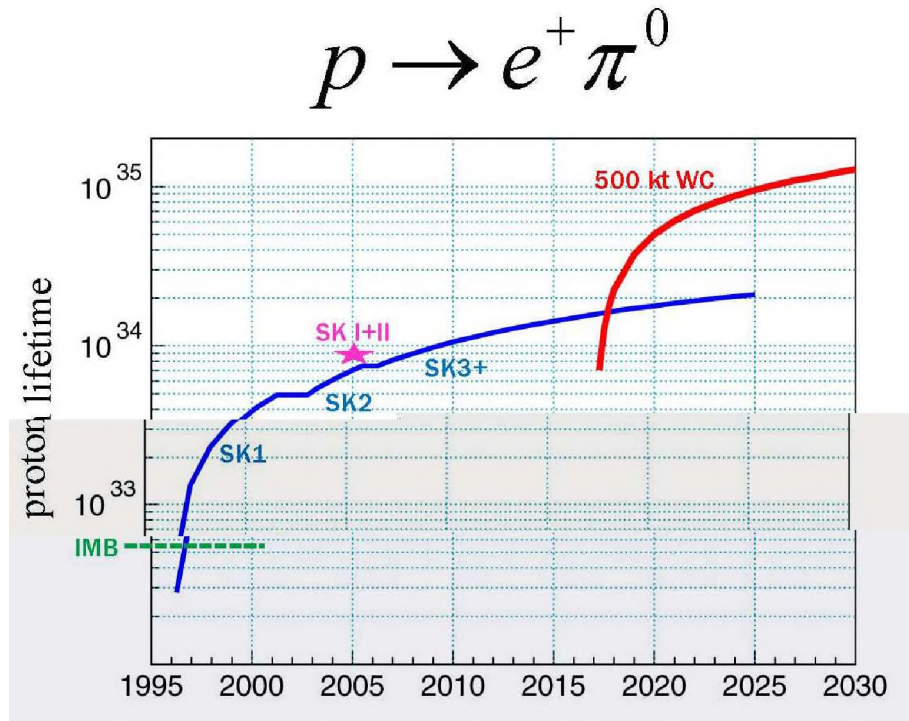
$$p \to e^+ \pi^0$$

FIG. 2: The blue line gives the present & future Super-K bounds (as a function of time) for the proton lifetime into the decay mode $p \to e^+ \pi^0$. The red line indicates the advantage of a half Megaton water Cherenkov detector. Courtesy of E. Kearns, NNN07 talk.

multi-prong experimental program which includes,

- proton decay,

- long baseline neutrino oscillations to measure the remaining unmeasured mixing angle, θ_{13}, and CP violation in the lepton sector, and

- the observation of astrophysical neutrinos, such as a near-by super-nova or relics of past super-novae.

Several large detectors, in different parts of the world, have also been proposed to continue the search for proton decay. These include, Hyper-Kamiokande in Japan and LAGUNA in Europe. Hyper-Kamiokande is a water Cherenkov detector, while LAGUNA is a European collaboration which is considering three possible technologies; water Cherenkov, liquid argon or liquid scintillators. These detectors, if built, have similar goals to any DUSEL detector, i.e. to reach a lifetime sensitivity of 10^{35} years.
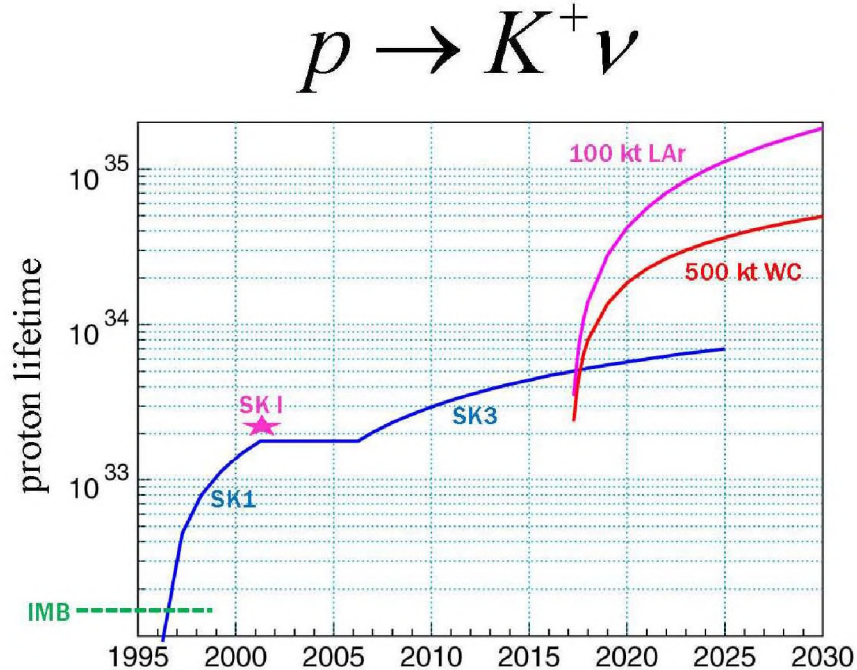
FIG. 3: The blue line gives the present & future Super-K bounds (as a function of time) for the proton lifetime into the decay mode $p \to K^+\nu$. The red (or magenta) line indicates the advantage of a 1/2 Megaton water Cherenkov (or 100 kton liquid argon) detector. Courtesy of E. Kearns, NNN07 talk.

It is thus crucial that the U.S. is a competitor in this super high energy frontier. This is not only to achieve the awesome science goals, but also to reap the benefits to our educational system and our culture that this search (*and discovery*) will bring. For this to be possible, we must start as soon as possible to construct a Megaton Observatory for Neutrinos and for Nucleon Decay.

G.   Summary

The Deep Underground Science and Engineering Laboratory (DUSEL), with a Large Megaton Size Detector, is desperately needed to address a set of fundamental issues in particle and astrophysics. The discovery potential of such a detector is high. It could of course be built in modules , each of about 140 kilotons. At least five such modules would be needed to achieve the desired goal. Because of its unique multi-purpose value and its physics significance, such a Large Size Detector at Homestake, coupled to a long baseline neutrino beam (which could be provided for example by Fermilab), would be one of the greatest assets to the U.S. and the world as a whole.

It would greatly complement the physics that may be learned from the forthcoming Large Hadron Collider and would thereby enhance the U.S. High Energy Physics efforts at the very highest energy frontiers.

III. LONG BASELINE NEUTRINO EXPERIMENT

A. Executive Summary

A continuing program designed to study CP violation in the neutrino sector and to determine the hierarchy of the neutrino mass spectrum is scientifically compelling. The US program may be unique in the world in its ability to measure the ordering of the neutrino mass spectrum.

CP violation has so far only been observed in the quark sector of the standard model. Its discovery in the neutrino sector should shed additional light on the role of CP violation in nature. Unveiling neutrino CP violation is particularly important because of its potential connection with the observed matter–antimatter asymmetry of our Universe, a fundamental problem at the heart of our existence. The leading explanation is currently a leptogenesis scenario in which decays of very heavy right–hand neutrinos created in the early Universe give rise to a lepton number asymmetry which later becomes a baryon–antibaryon asymmetry. Leptogenesis offers an elegant, natural explanation for the matter–antimatter asymmetry; but it requires some experimental confirmation of its various components before it can be accepted. Those include the existence of very heavy right–handed neutrinos as well as lepton number and CP violation in their decays.

A number of neutrino mass models have been proposed and precise knowledge of neutrino parameters is essential to test them. Specifically, the value of the mixing angle θ_{13} and the hierarchy of the neutrino mass spectrum will help distinguish between models based on lepton flavor symmetries, models with sequential right-handed neutrino dominance and more ambitious models based on Grand Unified Theory (GUT) symmetries. GUT models naturally yield a particular ordering of the neutrino spectrum and a relatively large θ_{13}.

The wide-band beam approach has a greater scientific reach for neutrino oscillations when located at a distance that permits resolution of the neutrino mass hierarchy, and further scope if the detector is located at a depth that permits the study of nucleon decay.

- The scientific goals of a program of long baseline neutrino oscillation experiments are to measure the mixing parameter $\sin^2 2\theta_{13}$, to determine the order of the states of the neutrino mass spectrum, and to determine whether there is CP violation in the neutrino sector. Measurement of these quantities is an important goal of elementary particle physics.

- Determination of the ordering of the neutrino mass spectrum, searching for CP violation, and resolution of parameter degeneracies with sensitivity down to $\sin^2 2\theta_{13} \simeq 0.01$ will require a new generation of experiments with detectors with mass of 100 kilotons or more. This

represents an increase in sensitivity of more than one order of magnitude over the experiments that will begin to acquire data in the next few years.

- The wide-band beam approach to neutrino oscillation physics can, in principle, utilize either a liquid argon detector or a water Cherenkov detector. If located more than 1000 km from Fermilab, there is good sensitivity for determining the mass hierarchy and measuring the amount of CP violation. The optimal baseline for a wide band beam experiment is between 1200 and 1500 km.

- Among experiments with super neutrino beams, wide band beam experiments have the most robust performance and the best mass hierarchy performance. Overall, they are the optimal choice to pursue after the near-future reactor and narrow band beam experiments.

B. Report on Neutrino Oscillations

Neutrinos, nearly massless and electrically neutral elementary particles, provide a unique window on the structure of matter at subatomic scales. They exist in three types: electron, muon and tau. In the past decade muon-neutrinos produced in cosmic ray reactions in the earth's atmosphere and electron-neutrinos produced in nuclear reactions in the sun's core have been shown to change from one kind to another between their source and detection. Further experimentation with both natural neutrino sources and neutrinos from reactors and accelerators has shown that the quantum mechanical mixing of neutrino types, also known as neutrino oscillations, is responsible for this change. A new generation of experiments has been initiated using reactor and accelerator neutrinos to make precise measurements of the mixing phenomena.

The discovery of neutrino oscillations showed that neutrinos have mass that are a million times smaller than the mass of the next lightest elementary particle, the electron. The reason the neutrino masses are so small is a fundamental issue that must be understood. It is expected that physics at energies much higher than those available in our laboratories are responsible for the origin of neutrino mass. Neutrinos are so abundant that the total mass of all the neutrinos in the Universe may be comparable to the total mass of all the stars in the Universe. Continuing studies of neutrinos will illuminate the most basic issues in physics at very small distance scales and at very large distance scales.

The three observed neutrino types, called flavors, couple to other particles with strengths given by the standard model of elementary particles. Th quantum mechanical mixing is parameterized

by three mixing angles, θ_{12}, θ_{23} and θ_{13}, and one phase angle, δ_{CP}, the so-called CP phase. The angle δ_{CP} describes how neutrinos and antineutrinos differ in their interactions with matter.

Neutrino oscillation phenomena depend on the four angles and the difference in the squares of masses (Δm^2) of the participating neutrinos. The discovery of atmospheric neutrino oscillations in the Super-Kamiokande experiment demonstrated that $\Delta m_{32}^2 \simeq \pm 2.5 \times 10^{-3} \text{eV}^2$ and mixing angle $\theta_{23} \simeq 45°$. These findings have been confirmed and made more precise by the MINOS experiment with an accelerator generated neutrino beam from Fermilab directed at a detector in the Soudan mine in Minnesota.

As yet, the sign of Δm_{32}^2 is undetermined. The so-called normal mass hierarchy, $m_1, m_2 < m_3$, suggests a positive sign which is often obtained in theoretical models. However, a negative value (or inverted hierarchy, $m_1, m_2 > m_3$) can certainly be accommodated, and if that is the case, the predicted rates for neutrinoless double beta decay will likely be larger and more easily accessible experimentally. Resolving the sign of the mass hierarchy is an extremely important issue. In addition, the fact that θ_{23} is large and near maximal is also significant for model building. Measuring that parameter with precision is highly desirable.

The deficit of observed neutrinos from the sun compared to expectations was a decades-long puzzle that has been definitively explained as due to oscillations of solar neutrinos as they propagate through the sun. From measurements of solar and reactor neutrino oscillations it has been found that $\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{eV}^2$ and $\theta_{12} \simeq 32°$. The sign of Δm_{21}^2 is known to be positive due to the effects of the solar medium on the propagation.

The mixing angles θ_{12} and θ_{23} are large relative to all of the mixing angles in the quark sector. The reason for the different patterns of mixing in the neutrino and quark sectors remains to be understood theoretically. In addition, Δm_{21}^2 is large enough, compared, to Δm_{32}^2, to make long baseline neutrino oscillation searches for CP violation feasible and could yield positive results, i.e. the stage is set for a future major discovery of CP violation in the lepton sector.

Currently, we know nothing about the value of the δ_{CP} and only have an upper bound on the as yet unknown mixing angle θ_{13} ($\theta_{13} < 13°$ or $\sin^2 2\theta_{13} \leq 0.2$). However, a survey of 63 models in the literature found that the predictions for θ_{13} were clustered around $\sin^2 2\theta_{13} = 0.04$ ($\sin^2 \theta_{13} = 0.01$), as displayed in Fig. 4. If $\sin^2 2\theta_{13}$ is comparable to or greater than this value, it is likely to be determined by the coming generation of reactor $\bar{\nu}_e$ disappearance experiments at Double CHOOZ (France) and Daya Bay China) and the upcoming accelerator based $nu_\mu \rightarrow \nu_e$ appearance experiments T2K (Japan, J-Parc to Super-Kamiokande) andNOνA (USA, Fermilab to Minnesota). Reactors experiments are complimentary to long-baseline experiments in that they
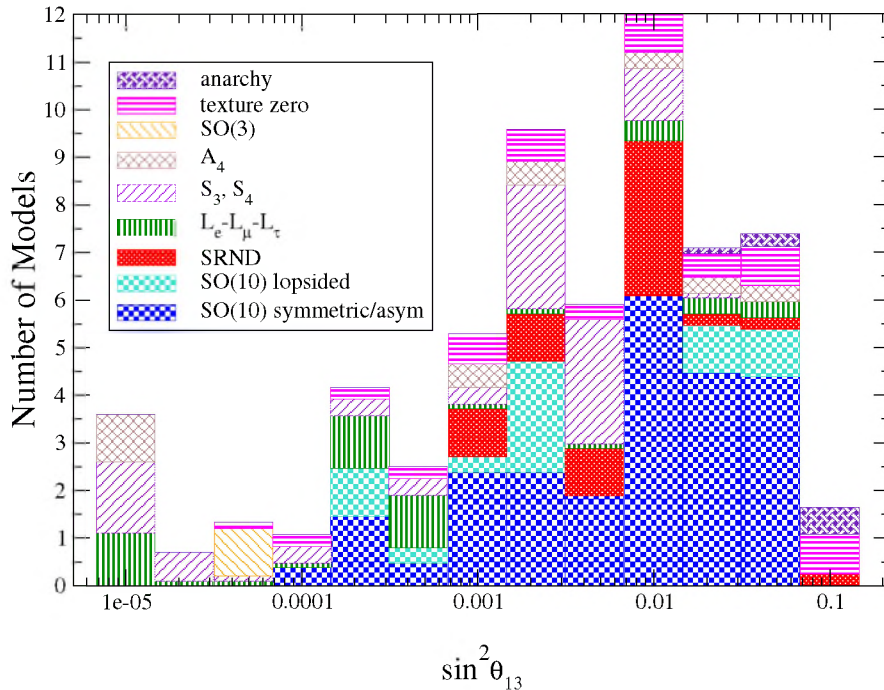
FIG. 4: Histogram of $\sin^2\theta_{13}$ predictions for 63 models. Source: C.H. Albright and M.C. Chen, arXiv:hep-ph/0608137.

can provide valuable information on θ_{13} but not on the mass hierarchy or δ_{CP}.

Based on our current knowledge and future goals, a future neutrino program should include the following objectives:

- Complete the measurement of the neutrino mixing angles,

- Determine the sign of Δm^2_{32},

- Measure δ_{CP} to determine if CP is violated,

- Search for exotic effects in neutrino oscillations.

Of the above future neutrino physics goals, the search for and study of CP violation is of primary importance and should be our main objective for several reasons, which we briefly address.

CP violation has so far only been observed in the quark sector of the standard model. Its discovery in the neutrino sector should shed additional light on the role of CP violation in nature. Unveiling neutrino CP violation is particularly important because of its potential connection with the observed matter–antimatter asymmetry of our Universe, a fundamental problem at the heart of our existence. The leading explanation is currently a leptogenesis scenario in which decays of very

heavy right hand neutrinos created in the early Universe give rise to a lepton number asymmetry which later becomes a baryon antibaryon asymmetry via the B-L conserving 't Hooft mechanism of the standard model at weak scale temperatures.

Leptogenesis offers an elegant, natural explanation for the matter antimatter asymmetry; but it requires some experimental confirmation of its various components before it can be accepted. Those include the existence of very heavy right handed neutrinos as well as lepton number and CP violation in their decays.

A number of neutrino mass models have been proposed and precise knowledge of neutrino parameters is essential to test them. Specifically, the value of the mixing angle θ_{13} and whether the mass hierarchy is normal or inverted will help distinguish between models based on lepton flavor symmetries, models with sequential right-handed neutrino dominance and more ambitious models based on Grand Unified Theory (GUT) symmetries. GUT models naturally yield a normal hierarchy and a relatively large θ_{13} (although in a few unified models, an inverted hierarchy can be obtained with fine-tuning).

Leptogenesis can naturally emerge in grand unified theories. Moreover, successful unification of the strong, weak and electromagnetic forces strongly suggests the existence of a supersymmetry and its associated new particles at the TeV scale. The lightest stable particle of supersymmetry is a leading candidate for dark matter in the Universe. Thus neutrino physics is intimately connected to the most interesting outstanding questions today that are to be explored at the Large Hadron Collider, dark matter detection experiments and the IceCube experiment (which is designed to look for very high energy neutrinos as they pass through the Antarctic ice cap).

Designing for CP violation studies in next generation neutrino programs has other important benefits. First, the degree of difficulty to establish CP violation is high but achievable. It requires an intense proton beam of about 1 2 MW and a very large detector, 100-500 kton Water Cherenkov (WC) or a liquid argon (LArTPC) detector of size ~ 100 kTon which could be equivalent in sensitivity due to its better performance. Water Cherenkov is an established technology, while liquid argon, which promises superior particle identification and control over backgrounds, is still under development. Such an ambitious infrastructure will allow very precise measurements of all neutrino oscillation parameters as well as the mass hierarchy via $\nu_\mu \to \nu_\mu$ disappearance and $\nu_\mu \to \nu_e$ appearance studies.

In order to make an unbiased comparison of the physics potentials of the experimental setups the sensitivities as functions of *exposure* may be compared, where exposure is defined to be $\mathcal{L} =$ detector mass [Mt] $\times$ target power [MW] $\times$ running time [10^7 s]. The relative merits of three

Setup	$t_\nu + t_{\bar\nu}$ [yr]	P_{Target} [MW]	L [km]	Detector technology	m_{Det} [kt]	$\mathcal{L}$
F2AR	3 + 3	1.13 ($\nu/\bar\nu$)	810	LArTPC	100	1.15
WBB	5 + 5	1 (ν) +2 ($\bar\nu$)	1290	LArTPC	100	2.55
T2KK	4 + 4	4	295+1050	WC	270+270	17.28
β-beam	4 + 4	n/a	730	WC	500	n/a
NuFact	4 + 4	4	3000+7500	Magn. iron calor.	50+50	n/a

TABLE I: Setups considered, neutrino t_ν and antineutrino $t_{\bar\nu}$ running times, corresponding target power P_{Target}, baseline L, detector technology, detector mass m_{Det}, and exposure $\mathcal{L}$ [Mt MW 10^7 s].

superbeam scenarios, beta beam (β-beam) experiment, and neutrino factory (NuFact) experiment, are listed in Table I. In Fig. 5 we show the discovery reaches for $\sin^2 2\theta_{13}$, CP violation, and normal mass hierarchy versus the exposure for a fraction of δ_{CP} of 0.5 (see figure caption). The experiments we considered are a future narrow-band beam experiment from Fermilab to Ash River (F2AR) with average neutrino energy $E_\nu = 2.6$ GeV, a wide-band beam experiment ($E_\nu = 2.6$), and a narrow-band beam experiment from Tokai to Kamioka and Korea (T2KK) with $E_\nu \simeq 0.8$ GeV.

If θ_{13} is not too small ($\sin^2 2\theta_{13} \simeq 0.01$), it may be possible to mount experiments that will permit us to determine the ordering of the states in the neutrino mass spectrum and to measure CP violation in the neutrino sector of the particle world. To pursue this goal a wide-band, on-axis, neutrino beam directed to a future Deep Underground Science and Engineering Laboratory site, needs to be developed. The fact that a very large underground detector can also be used to determine neutrino CP violation and measure all facets of neutrino oscillations gives such a facility an outstanding discovery potential.
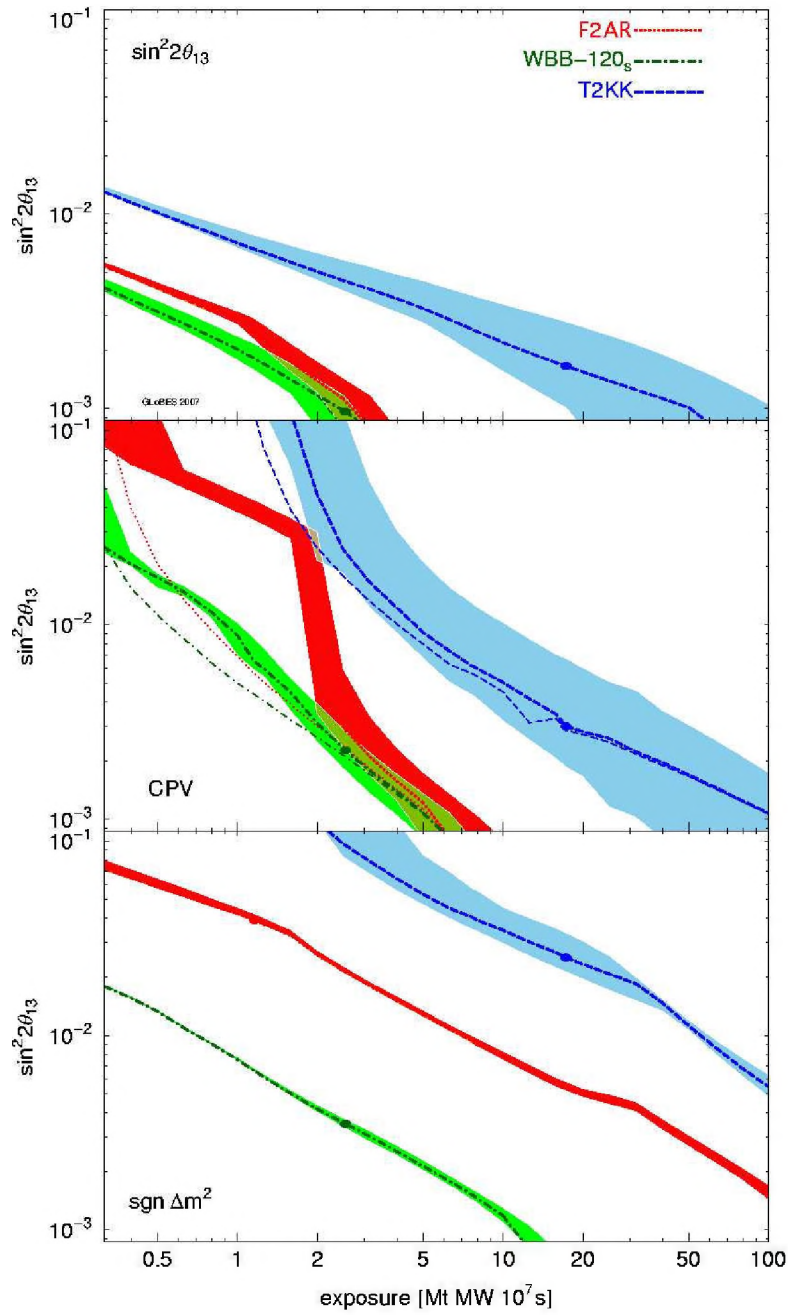
FIG. 5: The $\sin^2 2\theta_{13}$ reach at 3σ for the discovery of nonzero $\sin^2 2\theta_{13}$, CP violation, and the normal hierarchy as a function of exposure. The curves are for a fraction of δ_{CP} of 0.5, which means that the performance will be better for 50% of all values of δ_{CP}, and worse for the other 50%. The light curves in the CPV panel are made under the assumption that the mass hierarchy is known to be normal. The dots mark the exposures of the setups as defined in Table I. The shaded regions result by varying the systematic uncertainties from 2% (lower edge) to 10% (upper edge).

IV. ASTROPHYSICAL NEUTRINOS

A. Executive Summary

Until the 1950's visible light provided our only view of the Universe. Tremendous progress came in the following years when we extended our observational toolbox to the whole electromagnetic spectrum from microwaves to gamma rays. Recently a new window on the Universe has opened—neutrino astronomy and astrophysics—and there is hope that observing cosmological and astrophysical neutrinos, some from the most exciting electromagnetic sources in the Universe, will likewise expand our understanding. We are now able to detect neutrinos of astronomical origin with energies ranging from a few MeV (10^6 eV) to 10^{21} eV. The lower end of this energy range is accessible at underground laboratories whereas the higher end is accessible with huge neutrino telescopes such as IceCube or ANTARES, which use the Antarctic ice cap or the Mediterranean Sea, respectively. Astrophysical neutrinos help us explore fascinating phenomena in the Cosmos as diverse as the birth of new stars and the origin of elements. These neutrinos provide a new tool complementary to other tools already in place: various electromagnetic (optical or otherwise) telescopes, which can look at the photons coming from neutrino-emitting objects, or LIGO, which can measure gravitational collapse accompanying neutrinos. We have already seen neutrinos from two (and only two) such objects: A main-sequence star (the Sun) and a core-collapse supernova (SN1987A). In both cases, deep and fundamental understanding about the nature of the Universe resulted.

It should be emphasized that there is a large and active community of researchers in the U.S. to use DUSEL carrying out a program in this new neutrino astrophysics. Such an activity would be complementary to the very high-energy neutrino astronomy programs already in place with experiments such as IceCube. Recent accomplishments in this area include:

- Theoretical prediction of the solar neutrino flux and structure of the main sequence stars are confirmed by solar neutrino measurements, resulting in the Standard Solar Model. For example, the temperature at the center of the Sun was correctly calculated ab initio to better than 2%.

- Recognition of the importance of the neutrino-neutrino interactions on neutrino propagation in dense neutrino systems and the development of the theoretical tools to treat these effects in astrophysical sites. Thus core-collapse supernovae provide us with the only example of a non-trivial many-body system entirely controlled by weak interactions.

- New theoretical breakthroughs in understanding nucleosynthesis in supernovae and gamma-ray bursts as well as the role of weak interactions in supernova dynamics.

- Establishing that active neutrinos cannot be the dark matter, which is independently confirmed by cosmological data.

- Placing new limits on the diffuse supernova neutrino background. Reduced astrophysical uncertainties mean that these searches are primarily testing the neutrino emission per supernova. In fact, considering the significantly lower reactor neutrino and cosmic ray backgrounds at the 4850 ft. level of DUSEL compared to Super-Kamiokande and the use of Gadolinium, there is a strong likelihood of actually observing the diffuse supernova neutrino background.

B.   Report on Neutrino Astrophysics

The first example of neutrino astrophysics concerned neutrinos from the Sun. The solar neutrino program represents one of the great triumphs of physical science in the last 40 years and led to the Nobel Prize for Ray Davis in 2002. The story starts with an old question as to the origin of the sun's energy. The answer analyzed by Hans Bethe and others was that it came from nuclear fusion reactions which give off millions of times more energy than chemical reactions. Particularly due to the work of John Bahcall, it was realized that almost 3% of the energy comes off in neutrinos which could travel directly from the center of the Sun to the Earth and provide the *only* direct evidence of nuclear reactions that took place in the very core of the Sun.

The pioneering experiment of Ray Davis provided evidence for solar neutrinos but only one-third as many as the theory predicted. As a result of a number of subsequent experiments, physicists converged on an answer to this puzzle: two-thirds of the electron-neutrinos, the only kind produced in the Sun, had oscillated into the other types (muon or tau neutrinos). This conclusion was experimentally verified by combining the results of the SNO experiment in Canada in 2000 by the direct detection of the muon and tau neutrinos in a heavy-water Cherenkov detector, and the accurate measurement of solar neutrinos by many other experiments. Thus the results appeared to confirm our theory of the source of the Sun's energy and at the same time discovered new *particle physics beyond the standard model: neutrinos had mass.*

Much remains to be done in the study of solar neutrinos. Most experiments detect the highest-energy neutrinos which are only 2 out of 10,000 of the neutrinos that come from the sun. 85%

of solar neutrinos come from the reaction that starts off the chain of reactions in the sun: the weak reaction that fuses two protons together to form deuterium with the emission of an electron and neutrino. There is only indirect evidence for these neutrinos from the radiochemical gallium experiments in Russia and Italy, neither of which are able to measure the energy spectrum of these neutrinos There are several proposals for deep underground experiments that could detect these neutrinos and their energies. Such measurements would provide strong direct evidence that the particular series of fusion reactions proposed by Bethe are indeed the source of the Sun's energy. It would indeed be wonderful if these experiments were carried out at the Homestake site where Ray Davis pioneered the study of solar neutrinos. A real-time measurement of pp neutrinos can provide a 1% measurement of neutrino mixing($\sin^2 \theta_{12}$) as well as testing the sum rule connecting solar photon and neutrino luminosities. The latter test could constrain the possibility that subdominant neutrino sources may be present in the Sun.

For stars larger (and hotter) than the Sun the main source of energy is a different set of fusion reactions known as the CNO cycle. These reactions involve carbon, nitrogen and oxygen nuclei; as a result of their larger electric charge it takes higher energies for protons to overcome the Coulomb repulsion and so it is most effective in hotter stars. However calculations indicate that about 1% of the solar energy is produced by the CNO cycle. This produces a characteristic neutrino spectrum at higher energies than those from the proton-proton reaction so that proposed detectors may also be able to detect these in spite of their low flux. Detection of these CNO neutrinos would be direct evidence of the CNO cycle and would also be of great interest because it would provide information concerning the chemical composition near the center of the Sun. Measuring the core metallicity of the Sun could resolve some outstanding problems with helioseismology. It would also be valuable in confirming our theory of the CNO cycle, the major source of energy for larger stars.

The other great event of neutrino astronomy occurred in February of 1987. In a period of 10 seconds 19 neutrinos were observed from a type-II supernova in two small water Cerenkov detectors: 11 in Kamiokande in Japan and 8 in the IMB detector in the US. These neutrinos had been traveling for 150,000 years from outside our galaxy and arrived a couple of years after these detectors started to operate. From these 19 events it could be deduced that roughly 30 billion trillion trillion trillion trillion neutrinos had been emitted in that 10 second interval. A type-II supernova is believed to be the result of a sudden collapse of a star as a result of the depletion of its nuclear fuel. The core of the star collapses to nuclear density producing a huge amount of energy in the form of highly energetic particles, but the only particle that can get out is the weakly-interacting neutrino. Shortly after the collapse the star begins to shine extremely bright

in the sky with a luminosity 500 times that of the sun, but in fact theory tells us that 99% of the energy of collapse is emitted in neutrinos. This was roughly confirmed by the 19 neutrinos of 1987.

Sometime in the future there will be a supernova explosion in our own galaxy. This would produce many thousands of events in a detector the size of Super-Kamiokande. As larger underground detectors are installed they would naturally be part of a supernova watch designed to precisely measure the properties of these many thousands of events. Our understanding of the supernova process will be greatly increased by observations of the energy and timing of each of three types of neutrinos. Knowledge of the total energy carried out by neutrinos is important to understand the proceeding neutron star formation. The neutrinos we observe will clearly be affected by oscillations so that it will be better if we have good information on oscillation parameters. There may be a large sensitivity to $\sin^2 \theta_{13}$, the value of which may be determined by reactor neutrino experiments. We need to be able to make precision measurements of cooling time, timing of neutronization pulse, average energy and time-integrated luminosity and the neutrino spectrum. It is worth noting that neutrino observations of core-collapse supernovae and merger of neutron stars and other compact objects also provide a probe complementary to other U.S. scientific investments such as LIGO.

It is believed that in a core-collapse supernova many of the heavy elements in nature are first formed by what is called the r-process. The abundance of different elements and isotopes depends on the neutron-proton ratio at the site and this is influenced by the neutrino flux. Thus observations of supernova neutrinos may help us better understand the origin of elements. Megaton-scale detectors with a reach of about 10 megaparsecs may enable to search for supernovae in other galaxies without necessarily seeing the accompanying photons. While a supernova in our galaxy may not occur for many years it will be possible in megaton detectors to see a small number of neutrinos from many other galaxies. Thus interesting statistics on supernova neutrinos can be acquired. Core-collapse supernova physics nicely illustrates that astrophysical extremes allow testing neutrino properties in ways that cannot be done elsewhere, e.g. exploring the neutrino-neutrino interaction effect as an "emergent phenomenon".

Supernovae have been exploding for billions of years and they supply a diffuse background of neutrinos. The detection of the higher energy neutrinos in this background should be possible in a large deep underground detector. This will allow us to look back in time and gain information on the rate of star formation in the distant past, a unique window on the history of our Universe.

This is a new kind of astrophysics looking at the interior of compact objects. Even though neutrino observations are typically complementary to observing light, this does not necessarily have to be the case: There could always be something new. Finally it should be pointed out

that neutrino astrophysics is one of the most interesting basic science topics suitable for terascale computing applications

V. DARK MATTER DETECTOR

A. Executive Summary

The Universe is filled with a mysterious form of dark matter, the understanding of whose fundamental nature poses the greatest challenge to contemporary cosmology and particle physics. We argue that the best motivated dark matter models are on the verge of being explored by direct dark matter search experiments that would enormously benefit from a laboratory like DUSEL. Dark matter searches in DUSEL offer a unique opportunity for ground-breaking New Physics discoveries. The future laboratory will play a fundamental role in post-discovery dark matter studies, and in giving the United States a leading role in one of the hottest field in physics today.

B. Dark Matter

The nature and identity of matter in the Universe is one of the most persistent questions ever posed and one of the most challenging problems facing modern cosmology and particle physics. The wealth of evidence for a new form of matter from many very different types of observations is overwhelming. The first indication for dark matter came from the observations of high velocities of galaxies within clusters of galaxies which required an additional source of gravity beyond that which could be accounted for from light-producing galaxies in the cluster. Similarly, the rotation of stars and gas in spiral galaxies also pointed to the notion that galaxies were embedded in a large and massive halo of dark gravitating matter.

More recent observations have bolstered the necessity for the existence of dark matter. Large amounts of gas (mostly hydrogen and helium) around galaxies and clusters of galaxies tend to be very hot (of order a few million degrees). At these temperatures, the gas emits electromagnetic radiation in the X-ray frequency bands which have been observed by X-ray satellites. The presence of this gas requires a significant amount of gravity to prevent the hot gas from flying off into space, in turn yet another indirect evidence for dark matter.

It is also known that gravity can bend the path of light. Observations of distant galaxies along the line of sight of a large cluster of galaxies shows clear signs of the gravitational lensing of the light. Indeed, recent claims to direct evidence for dark matter came from observations of a collision of clusters of galaxies showing lensing which is directly associated with (non-dissipative) dark matter in tact with the two clusters whereas the (dissipative) hot gas has been stripped from the cluster by the collision.

Our theoretical understanding of the very existence of galaxies and structure in the Universe itself also relies on the existence of dark matter. The initial seeds or perturbations in an otherwise smooth and homogeneous Universe could not have grown sufficiently to produce galaxies and clusters without a dark matter component. Evidence for the imprint of these seeds have been left on the microwave background radiation, and detailed measurements by many experiments have precisely determined several of the key parameters describing our Universe including the abundance of dark matter. All of these measurements are completely consistent both qualitatively and quantitatively with the fact that dark matter dominates the overall matter budget of the Universe.

All of the experiments and astronomical observations which have established the existence of dark matter are to date incapable of determining the identity and fundamental nature of the dark matter particle. In principle, one could imagine that the dark matter is simply some form of ordinary matter (*i.e.* made of neutrons and protons), in a non-luminous state (such as a dead star or perhaps dust). While there are many astrophysical constraints against such objects, our understanding of the early Universe through nucleosynthesis (the process of formation of the light elements, Deuterium, Helium, and Lithium) places a firm limit on the total amount of normal matter which is far below the requisite amount of dark matter. Furthermore detailed analysis by the WMAP experiment observing microwave background anisotropies has firmly established the relative amounts of total matter (normal plus dark) to normal matter.

Another possibility for dark matter among known particles in physics is the neutrino, now known to have a small but finite mass. However, it has also been established that the neutrino abundance can comprise less than 1% of the matter density.

We are led to the conclusion, therefore, that the predominant form of matter in the Universe can not be composed of normal matter (*i.e.* made of protons and neutrons) and must be related to physics beyond the standard (and well established) model of strong and electro-weak interactions. The distribution of the known components of matter with the abundance of dark matter (*i.e.* excluding dark energy, the non-clustering component of the Universe) is shown in Fig. 6.

The theoretical literature contains many new physics models that also contain candidate cold dark matter (CDM) particles. Some of the many candidate CDM particles include: axions, sterile neutrinos, weakly interacting massive particles (WIMPs), SuperWIMPs, Q-balls, black hole remnants and fuzzy cold dark matter. Out of this list, axions and WIMPs stand out in that they occur as by-products of theories which solve longstanding theoretical problems with the standard model. Axions occur in models which solving an important quantum problem associated with the

The Matter Content of the Universe - 2008

- ■ Dark Matter (83.3%)
- ■ Free H and He (13.8%)
- □ Stars (1.7%)
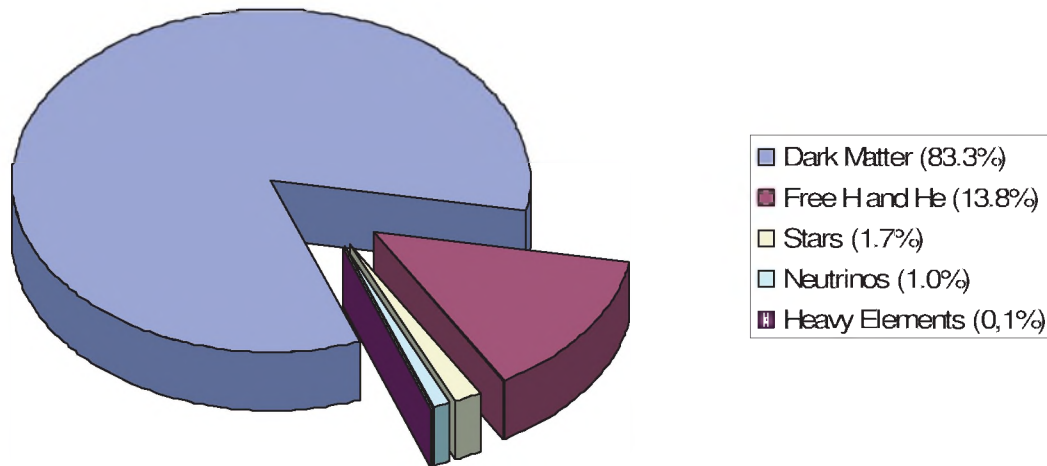- □ Neutrinos (1.0%)
- ▣ Heavy Elements (0,1%)

FIG. 6: The pie chart shows the relative abundance of different components of matter.

strong nuclear force. Axions can be searched for in terrestrial experiments using microwave cavities. WIMP particles typically occur in theories which attempt to explain the mechanism behind the breakdown of the electro-weak symmetry (the symmetry relating electromagnetism to the weak nuclear force). WIMPs are especially compelling in that a calculation of their relic abundance from production during the Big Bang falls very close to the measured abundance if the particles are weakly interacting, and have mass of order 100 times the proton mass and is of order the weak scale. This fact can be construed as independent *astrophysical* evidence for the existence of new physics at the weak scale.

There are many examples of WIMP particles. Candidates arising from supersymmetric (SUSY) theories– due to their deep connection with grand unified and superstring theories, along with some indirect experimental support– have been most thoroughly examined. SUSY theories posit that each known particle has a superpartner with mass of order the weak scale. The superpartners arise due to the intrinsic Fermi-Bose symmetry that is the foundation of SUSY theories.

The CERN LHC which just turned on—with proton-proton collisions at a record 14 trillion

electron Volts should have enough energy to produce the superpartners directly in a laboratory environment. The superpartners are expected to decay via a cascade of particles which includes the lightest SUSY particle, which is the CDM candidate. The presence of collider events with large missing energy beyond that expected from the standard model would signal the production of dark matter at the LHC. A measurement of various properties of the superparticles would allow one to determine the nature of the SUSY model, and measure properties such as the mass of the CDM particle.

Relic WIMPs can also be detected indirectly. In one instance, the sun, as it follows its path through the galaxy, may actually sweep up WIMP particles which then collect at high density in the solar core. The high density core WIMPs may then annihilate one with another into standard model particles, including neutrinos with very high energies. The proton decay search facility to be housed in DUSEL will also have dramatic consequences for dark matter searches, as it would allow to look for these energetic neutrinos produced in WIMP annihilations in the center of the Sun or of the Earth. In many respects, this facility would go beyond the reach of experiments like IceCube, situated at the south pole, in this search technique, and be complimentary to direct detection.

WIMPs circulating in the galactic halo may also occasionally annihilate one-with-another. Annihilation products such as gamma rays and anti-matter particles can be detected at various ground and space-based detectors. Gamma rays have the advantage in that they would point directly back to the spot at which the annihilations occur. A knowledge of WIMP properties gained from direct detection and collider searches, combined with gamma ray data from WIMP halo annihilations could allow for dark matter tomography measurements of the galactic dark matter density distribution.

Dark matter particles left over from the Big Bang may also be detected directly via their collisions with nuclei in low background environments located deep underground (generally, the deeper the better), an outstanding example being DUSEL. In fact, direct WIMP detection is in every way complementary to detection at the LH—in part because direct detection would verify that the missing energy particles found in LHC collisions would actually be dark matter particles—and to indirect detection, being free of the complicated intrinsic astrophysical backgrounds that hinder the possibility of firmly establishing an anomalous indirect signal as coming from dark matter.

The field of direct dark matter detection has recently succeeded in achieving major progress in sensitivity and in demonstrating the feasibility to scale up the size and performance of current

experiments. In addition, several different techniques are being successfully explored, including solid state, noble gas and bubble chamber detectors. The CDMS-II and Xenon-10 collaborations – employing two different target nuclei—reported comparable extremely competitive new sensitivity limits. These new limits are triggering a lively reaction in the particle and astro-particle theory community, as for the first time well-motivated particle dark matter models are being explored and constrained.

While it is hard to quote a model-independent *lower limit* on the expected signal from scattering of dark matter off nuclei, the exploration of the parameter space of theoretically motivated particle dark matter theories and independent arguments based on the observed abundance of dark matter in the Universe indicate that a signal is to be expected in the range between the current sensitivity and what is anticipated to be possible in experiments at DUSEL. The generic expectation for some of the best understood and motivated particle physics models for CDM—including SUSY—is that a large fraction of models lies between the current sensitivity and the sensitivity that current experimental techniques could achieve in DUSEL at the 4850 ft depth level. Most of the models with a faint predicted signal should be explored in DUSEL at the 7400 ft depth level with large (ton-sized) detectors. Even a non-detection would have profound consequences if such sensitivities are achieved.

The most general possible interaction between a nucleus and a WIMP includes in the non-relativistic limit a coherent spin-independent coupliing (scaling as A^2, where A is the target nucleus atomic number) plus a spin-dependent coupling. In general, theory indicates that spin-independent scattering on large A nuclei is the most promising direct dark matter detection technique. Models exist, however, where the spin dependent cross section is a better detection channel.

The implications of direct detection of dark matter would be formidable, and would open a new chapter in the history of Science. The high-energy and astro-particle theory community believes that DUSEL will be important—if not fundamental—both at the stage of discovery and in the subsequent phase of study of the properties of the dark matter particle. If a dark matter signal is detected, the discovery will need to be both confirmed by other experiments and reproduced. As the reported detection of dark matter by the DAMA collaboration has taught the community, systematic uncertainties and backgrounds are a problematic issue, and likely depend on environment: in this respect it will be essential to have more than one facility where to run direct dark matter detection experiments. Having a large underground laboratory will allow a multi-pronged approach, which will make use of several experimental techniques and different target materials. This will entail the possibility of confirming a detected signal rate, if studying the recoil spectral

shape, investigating the A^2 scaling with nuclear number. In turn, This will ultimately make it possible to measure the interactions of dark matter with ordinary matter and to estimate the particle dark matter mass independently of colliders. In addition, any claim of periodicity (day/night or seasonal) will benefit from the simultaneous operation of two or more detectors.

As alluded to above, models exist where spin-dependent searches are the only way to detect a dark matter signal. Having at disposal a large underground facility would allow to set up this second category of experiments, whose performance has been shown to be in many ways complementary to spin-independent searches, and whose results can yield important information on the spin of the dark matter particle. Furthermore, it was shown that measuring the ratio of spin-independent to spin-dependent scattering rates with at least two targets can lead to the discrimination of, for example, supersymmetric and extra-dimensional models.

Along similar lines, a deep underground laboratory might allow the development of dark matter search experiments requiring strong cosmic ray background suppression that could explore alternative dark matter particle scenarios. For instance, special experiments would be needed to explore super-light dark matter scenarios, and if underground space allows, could be hosted in DUSEL.

The detection of a signal will usher in an era of dark matter astronomy, in which we will be able to study the dark sector of the Universe directly. It will become feasible to directly observe the structure of the dark matter halo, and answer questions like: how much dark matter is there in our galaxy, in particular near the Solar System? Is dark matter concentrated in clouds or is it smoothly spread out all over the galaxy? Are there streams of dark matter like our current theories predict? Data from direct detection experiments at DUSEL will be combined with other data on the galactic halo to arrive at an understanding of how our galaxy formed. For example, the GLAST space-born gamma-ray telescope may detect the emission from dark matter in the halo, and observational programs in the Sloan Digital Sky Survey will detect and measure stellar structures and motions in the galactic halo.

In a possible scenario, the Large Hadron Collider discovers a new particle that theorists determine is suitable to be the dark matter. At the same time, direct detection experiments at DUSEL observe particles from outside the Solar System and confirm that the particles discovered at the Collider is indeed the dark matter. While dark matter experiments at DUSEL go on to measure the density of dark matter in the vicinity of the Sun, other indirect dark matter searches map the amount and location of dark matter in our galaxy. Further directional detectors at DUSEL measure the velocities and arrival directions of the dark matter particles. Theoretical studies ascertain that these velocities are consistent with the results of indirect searches. This brings direct evidence

of streams of dark matter swirling in the galactic halo, directly confirming the idea that galaxies are formed by combining small dark matter clouds into larger and larger structures.

The theory community is greatly excited by the prospective of DUSEL since this would create a center for dark matter studies in the United States. Laboratories have always, in the history of particle physics, triggered very fruitful interactions among theorists and between theorists and experimentalists. Theory workshops could be hosted at DUSEL, as well as yearly executive summaries of theoretical progress for experimentalists and of experimental progress for theorists.

Finally, in the forthcoming era of large direct detection collaborations, it will be strategic for the US scientific community to have a laboratory like DUSEL in the US, preventing the risk of a drain of human resources outside the country, with dangerous consequences in particular for the theory community.

VI.   NEUTRINOLESS DOUBLE-BETA DECAY

A.   Executive Summary

The neutrino is an elementary particle that scatters only through the weak interaction, and consequently rarely interacts in matter. Neutrinos carry no electric charge, have spin one-half, and belong to a family of particles called leptons. Leptons are particles which interact via weak, electromagnetic or gravitational forces only. The electron and electron neutrino are leptons with lepton charge, $L = +1$. Their anti-particles have lepton charge, $L = -1$. Neutrinos differ from quarks, which have both strong and electromagnetic interactions, and from other leptons, such as the electron, which are charged and thus interact electromagnetically.

Owing to the rarity of their interactions, the neutrinos are elusive. Studying them experimentally is a major challenge. While their existence was first postulated almost 80 years ago, it took 25 years to detect them in the laboratory. Only recently have high-precision neutrino experiments been possible. One fact established from experiments of the past decade is that, contrary to the prediction of the otherwise well confirmed standard model of the elementary particles, neutrinos are not massless. But their masses are extremely tiny: a neutrino is at least a million times lighter than the next lightest particle, the electron.

The most natural explanation for the lightness of neutrinos, compared to all other particles, is the so-called See-Saw Mechanism. The See-Saw Mechanism is only possible for electrically neutral particles, which can, in principle, be their own anti-particles. The mass term for such a particle can include what is known as a Majorana mass. The irony of the See-Saw Mechanism is that neutrinos are so very light due to the existence of a very heavy mass, $M \gg M_W$. In fact, M is so very large that it is close to the grand unification scale where the electromagnetic, weak and strong interactions are equal. In fact neutrino masses may be another indication of grand unification and supersymmmtry. Neutrinoless double beta decay experiments can prove that the neutrino has a Majorana mass and is its own anti-particle.

B.   Neutrinoless Double Beta Decay and the Origin of Mass

The question of the origin of masses, for the neutrinos and everything else, is one of the central puzzles of elementary particle physics. Several observations—the extreme lightness of the neutrinos, their electrical neutrality, and important theoretical principles—suggest that the mechanism generating neutrino masses differs from that generating other particle masses. Because neutrinos

are neutral, a neutrino can serve as its own antiparticle: consequently, unlike other leptons and unlike the quarks, neutrinos can possess so-called Majorana masses. This kind of mass, when added to the Dirac mass that neutrinos (and other Standard-Model particles) can have, can account (through the See-Saw Mechanism) for the tiny but nonzero neutrino masses found experimentally.

The only known feasible way to try to confirm that the neutrino has a Majorana mass (and thus lacks a distinct antiparticle) is to search for neutrinoless double beta decay—the process $(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-$, in which a parent atomic nucleus with N neutrons and Z protons decays to a daughter nucleus $(N - 2, Z + 2)$ plus two electrons. The observation of this process at any nonzero level would establish that neutrinos do possess Majorana masses and that they are indeed their own antiparticles. Majorana neutrino masses, if present, must arise from new physics beyond the standard model, very likely at a high mass scale far beyond the scale described by the standard model, and far beyond that accessible to the Large Hadron Collider (LHC) at CERN. Thus, neutrinoless double beta decay seeks mass-related new physics that would be invisible to the LHC.

One of the most conspicuous features of the Universe is that it contains atoms, of which we are made, but essentially no anti-atoms, which, had they been present, would have annihilated us. A leading candidate for the explanation of this crucial asymmetry is Leptogenesis, which states that the asymmetry arose from the decays of very heavy neutrinos that existed in the early Universe. Leptogenesis is an outgrowth of the See-Saw Mechanism, the leading candidate for the explanation of the incredible lightness of today's neutrinos. A signature feature of the See-Saw Mechanism and Leptogenesis is the prediction that neutrinos are their own antiparticles. Thus, the observation of neutrinoless double beta decay would provide evidence supporting both the See-Saw Mechanism and Leptogenesis.

The observation of neutrinoless double beta decay, $(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-$, would also demonstrate that *lepton charge* is not conserved : a final state containing two leptons is produced from an initial state containing none. This non-conservation would remove one of the principles protecting the proton from decaying into lighter particles. Slow proton decay, predicted by the theories that seek to unify the forces of nature, would eventually leave the Universe a very different place than it is now. Confirmation that protons do decay is a major goal of the very large underground detectors that would also study neutrinos from a distant accelerator.

It is likely that neutrinoless double beta decay, if it occurs, is dominated by physics that makes its rate proportional to $m_{\beta\beta}^2$, where $m_{\beta\beta}$, the effective Majorana mass for neutrinoless double beta decay, is a linear combination of neutrino masses. Thus, a measured value of the rate would
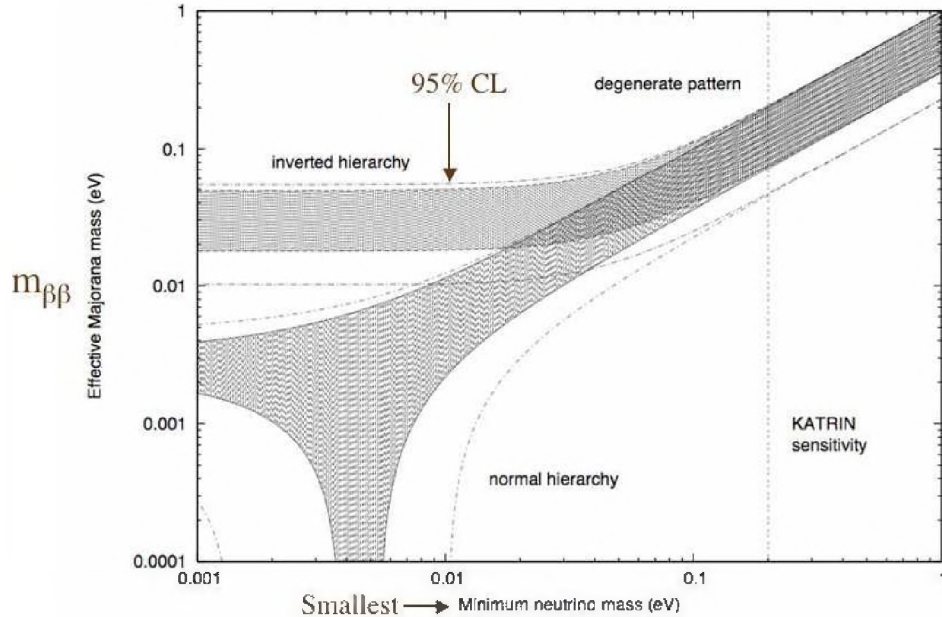
FIG. 7: The effective neutrino mass $m_{\beta\beta}$ observable in neutrinoless double beta decay experiments as a function of the smallest neutrino mass for both the normal and inverted neutrino mass hierarchy.

provide information on neutrino masses—information of a kind that cannot come from experiments on neutrino oscillations. While all of our current evidence for neutrino mass comes from oscillations, such experiments can only provide information on mass squared differences, not on absolute masses.

The sensitivity that an experiment needs to achieve in order to detect neutrinoless double beta decay depends on the value of $m_{\beta\beta}$. The possible values of $m_{\beta\beta}$, in electron volts, are shown in Fig. 7 as a function of the mass of the lightest neutrino. This figure assumes that there are three distinct neutrinos of definite mass, an assumption in accord with experiments done to date. From neutrino oscillation data, we know that the mass squared difference between the first and second neutrino is about 30 times smaller than that between this pair and the third neutrino. These results allow two mass patterns. If the closely spaced pair is at the bottom of the spectrum, the neutrino mass pattern is called the *normal* hierarchy, as it then resembles the quark spectrum. The alternative—the closely spaced pair at the top—is called the *inverted* hierarchy. If all neutrinos were much heavier than their mass differences, both the normal and inverted hierarchies would appear as three nearly degenerate neutrinos.

¿From Fig. 7, we see that if the hierarchy is inverted, $m_{\beta\beta}$ cannot be smaller than 0.01 eV. From the standpoint of theory, the inverted and normal hierarchies are equally likely. Thus, a very reasonable goal for the next generation of experiments is to be sensitive to $m_{\beta\beta}$ down to 0.01 eV, so that the inverted-hierarchy possibility will be fully covered.

The rate for neutrinoless double beta decay of a particular parent nucleus is proportional, not only to $m_{\beta\beta}^2$, but also to the square of a nuclear matrix element involving the wave functions of the parent and daughter nuclei and the nuclear operator for double beta decay. This matrix element must be taken from theory, which presently is uncertain by about a factor of two, judging from the spread in various predictions. Consequently, there is a significant theory uncertainty in estimating the decay rate that would correspond to a given value of $m_{\beta\beta}$. Neutrinoless double beta decay rates also vary substantially from nucleus to nucleus due to differences in the energy released in the decay. But in favorable cases where the energy release is large, one expects neutrinoless double beta decay lifetimes on the order of 10^{28} years for $m_{\beta\beta} \approx 0.01$ eV. This long lifetime, longer than any decay lifetime measured in any process to date, makes searches for neutrinoless double beta decay very challenging. Experiments require very large detectors, e.g., 1-10 tons of the parent isotope, and extraordinary efforts to eliminate backgrounds from cosmic rays and natural radioactivity. Achieving sensitivity to much of the $m_{\beta\beta}$ region allowed by a *normal* hierarchy will require still larger experiments, ones with hundreds of tons of parent material.

If the hierarchy is known to be inverted, and one achieves sensitivity to 0.01 eV but finds no double beta decay, then either neutrinos are not their own antiparticles, or some interesting new physics beyond that which leads to Fig. 7 is at work. Neutrinoless double beta decay is sensitive not only to neutrino mass, but also to various exotic forms of lepton charge violation that are found in some extensions of the standard model. Several of these exotic mechanisms are connected with supersymmetry, a symmetry predicting the existence of many new particles, partners of those found in the standard model. Finding these new particles is one of the major goals of the LHC. Were the LHC to make such a discovery, there would be intense interest in neutrinoless double beta decay mechanisms that arise from supersymmetry.

Experiments currently under development hope to cover most of the $m_{\beta\beta}$ region allowed by the inverted hierarchy. Both the technologies employed and the parent isotopes chosen for these experiments are quite varied. The latter is important, eliminating the possibility that an unfortunate parent isotope choice, one with a suppressed nuclear matrix element, could invalidate the conclusions of an experiment. The best current limits on neutrinoless double beta decay come from experiments using germanium detectors enriched in the double-beta decay isotope of interest, [76]Ge. New experiments scaling up this technology by factors of 10 to 100 are under development in both Europe and the US. Other new efforts include cryogenic arrays of ultra-sensitive TeO_2 bolometers, in which the decay of the parent isotope, [130]Te, can be seen, and a liquid xenon detector whose prototype is under construction at WIPP. The xenon detector, when fully developed, will employ

a novel atomic physics technique to detect the daughter nucleus ^{136}Ba produced in the decay of ^{136}Xe, making this experiment unusually insensitive to backgrounds. While many other efforts are underway, the three mentioned here include many U.S. physicists among the proponents.

If such next-generation experiments fail to detect neutrinoless double beta decay, next-to-next generation experiments at the 100-ton scale would likely become the next goal. Indeed, some of the experiments now under development hope to be scalable to still larger masses. Alternatively, if next-generation experiments discover neutrinoless double beta decay, more demanding follow-up experiments would still be needed, to probe the underlying mechanism. More information can be gained by studying which daughter-nucleus states are populated in the decay and by measuring the energy spectrum and angular correlation of the outgoing electrons.

Because next-generation experiments will be so challenging, it is important to have multiple efforts, to guard against an unidentified background producing a false result. Were several experiments to find neutrinoless double beta decay, this would not only confirm the result but also help theorists translate the rates into a reliable $m_{\beta\beta}$. Uncertainties in estimated nuclear matrix elements can be better assessed if predictions connected with a single $m_{\beta\beta}$ can be tested in several nuclei.

In summary, the search for neutrinoless double beta decay probes the physics of mass, in a way that is completely different from, and complementary to, the LHC program. A positive result would establish that neutrinos have Majorana masses and are their own antiparticles, distinguishing them from all the other constituents of matter. It would show that lepton charge is not conserved. The observation of neutrinoless double beta decay would demonstrate the physics necessary to both the See-Saw Mechanism and Leptogenesis. It would also remove one of the protections against proton decay. The search for neutrinoless double beta decay is inherently interdisciplinary, involving techniques and concepts from particle, nuclear, and condensed matter physics. To date, apart from one controversial claim, neutrinoless double beta decay has not been observed. But we now know that an interesting mass range is within reach of next-generation detectors, given what has been learned about neutrino mass from oscillation experiments. These detectors will not only be of unprecedented scale, but also require a degree of background suppression not yet achieved in physics.

VII. NEUTRON-ANTI-NEUTRON OSCILLATIONS

A. Executive Summary

The process of neutron–antineutron $(n - \bar{n})$ oscillation is an important way to probe the basic instability of matter that is believed to be at the heart of our understanding the origin of matter in the Universe as well as the nature of new forces responsible for neutrino masses. It complements the searches for proton decay, which have been conducted for the past two decades and are ongoing. At the Deep Underground Science and Engineering Laboratory, $n - \bar{n}$ oscillation time scales of order 10^{10} sec. can be probed, with the potential to reveal answers to many fundamental questions in elementary particle physics, with implications for nuclear physics, cosmology and astrophysics: Is the neutron its own antiparticle? What is the degree of instability of matter? What is the basic mechanism for the creation of matter over antimatter in the Universe? Are there extra space–like dimensions? Is there a hidden "parallel" Universe? What is the nature of dark matter in the Universe?

B. Introduction

A key concept that has emerged from recent theoretical studies seeking the ultimate unity of matter and forces is that at the fundamental level, matter is predicted to be unstable. The apparent stability of the Universe is a consequence of the fact that matter instability occurs on a time scale which is more than a trillion trillion (10^{24}) times the age of the Universe. A further argument that reinforces this belief is the realization during the past four decades that matter instability is indeed essential if one wants to understand why the observed Universe is made only of matter and no antimatter. The challenge for physics is to discover how matter instability manifests itself and what the degree of this instability is.

There are two known ways in which matter instability can be manifest: (i) the decay of a proton (or a neutron which is otherwise stably bound in a nucleus), discussed in another part of the white paper, and (ii) spontaneous conversion of neutron (n) to anti–neutron $(\bar{n})$, called $n - \bar{n}$ oscillation (see Fig. 8), the subject of this part of the white paper. Spontaneous conversion of other electrically neutral particles such as K-,B-meson into their antiparticles has already been experimentally established, providing ground-breaking information about the fundamental forces and constituents of matter. They have guided the course of elementary particle physics for the past half-century. The $n - \bar{n}$ oscillation is even more profound and is expected to provide insight

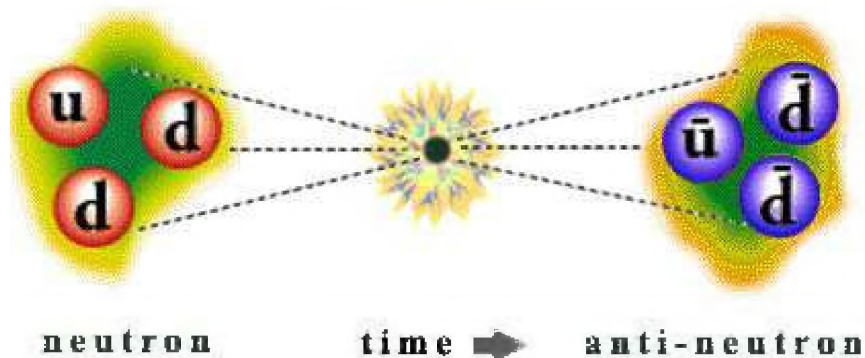into many fundamental issues confronting particle physics today.

FIG. 8: Neutron oscillating into anti-neutron.

It was pointed out in the early 1970's that since a neutron (n) is electrically neutral, it could convert itself to an anti-neutron ($\bar{n}$), and, moreover, that this conversion process could provide a way to understand the observed fact that there is an asymmetry between the amount of matter and antimatter in the Universe. In the early 1980's, reasonable and consistent particle physics models were discovered which predicted that neutrons are their own anti-particles, similar to massive neutrinos being their own anti-particles, and that $n - \bar{n}$ oscillation should occur at an observable rate. This led to increased experimental as well as theoretical interest in this process. The existence of free $n - \bar{n}$ oscillations would also mean that neutrons inside nuclei would become anti-neutrons and make nuclei unstable. However, due to the difference between the way neutrons and anti-neutrons behave in the presence of nuclear forces, matter stability is highly suppressed. As a result, oscillation times of a year would correspond to about 10^{30} years for nuclear instability. Ongoing proton decay experiments also found lower limits on nuclear instability time scales due to $n - \bar{n}$ oscillation in nuclei in the same range. It was realized that available reactor neutrons could be used to probe $n - \bar{n}$ oscillations with oscillation times precisely in the range of a year to few years. There are, however, severe limitations to discovering $n - \bar{n}$ oscillations inside nuclei, due to atmospheric neutrino backgrounds. Uncertainties concerning the relevant nuclear properties also make it difficult to pin down precisely the value of the oscillation time. Thus it seems that the most promising way to search for this process further is to search for $n - \bar{n}$ oscillations with free neutrons. This is what we propose to carry out at the DUSEL facility.

C. Present experimental situation

The only free $n - \bar{n}$ oscillation experiment carried out to date was at the European laboratory at Institut Laue-Langevin (ILL), where a lower limit on the oscillation time scales of $\tau_{n-\bar{n}} > 0.86 \times 10^8$ sec (90 % CL) was established. This lower limit can be interpreted as follows. A free neutron, which itself is unstable with a mean lifetime of $\tau_n = 886 \pm 1$ sec., does not oscillate to an anti-neutron in the time span of 0.86×10^8 sec. (or 2.7 years). There are theoretical reasons to believe that an oscillation time which is a factor of 100 above this limit could probe some very interesting new ideas in physics beyond the standard model.

As noted earlier, the oscillation rate of a free neutron in vacuum can be much faster than that inside a nucleus, where it is suppressed by internuclear forces. In fact, analysis of $n - \bar{n}$ oscillations in matter yields the relation between the free neutron oscillation time and the nuclear neutron oscillation time given by $\tau_{nuc} = R\tau_{n-\bar{n}}^2$, where R is a nucleus-dependent factor. Detailed nuclear physics calculations yield $R(^{16}O) \simeq 0.5 \times 10^{23}$ s^{-1} and $R(^{56}Fe) \simeq 0.7 \times 10^{23}$ s^{-1}. So the current lower bound on the free neutron oscillation time, $\tau_{n-\bar{n}} > 0.86 \times 10^8$ sec., corresponds to a lower limit on the nuclear decay time of about $\tau_{nuc} \gtrsim 1 \times 10^{31}$ yrs. Recent and ongoing proton decay searches are sensitive to similar lifetimes for the $n - \bar{n}$ oscillation mode. The Soudan-2 experiment has reported a lower limit $\tau_{nuc} > 0.72 \times 10^{32}$ yrs., which corresponds to the lower bound $\tau_{n-\bar{n}} \gtrsim 2 \times 10^8$ sec. Therefore, such an apparently small free neutron oscillation time is not in conflict with matter stability bounds.

D. Why is it important to conduct a high sensitivity search for $n - \bar{n}$ oscillation at DUSEL?

There are several reasons to conduct a high-sensitivity search for $n - \bar{n}$ oscillations, as enumerated below. DUSEL would serve as an ideal site for this search.

Why are the conventional proton decay search experiments not adequate?

If $n - \bar{n}$ oscillations exist, a neutron inside the nucleus could oscillate to an anti-neutron, which would subsequently annihilate with surrounding nucleons to give typically five pions with an invariant mass of two GeV. This will make nuclei unstable. Thus, in principle, conventional searches for proton decay (and decays of neutrons otherwise stably bound in nuclei) can probe for $n - \bar{n}$ oscillations. The relation $\tau_{nuc.} = R\tau_{n-\bar{n}}^2$ enables one to deduce the limit or value for $\tau_{n-\bar{n}}$ from the limit or value for the nuclear instability time τ_{nuc}. However, proton decay experiments are not

a very sensitive way to probe $\tau_{n-\bar{n}}$, compared to a direct search, for the following reasons. The first point is that an order-of-magnitude increase in τ_{nuc} only leads to a factor of three improvement in $\tau_{n-\bar{n}}$. More importantly, because of the presence of backgrounds, the lower limits on τ_{nuc} that can be derived go at most like the square root of the exposure time. Hence, if the fiducial volume of the proton decay search detector increases by a factor of 25 (as is being contemplated for the next generation of proton decay searches), the lower limit on τ_{nuc} will increase at most by a factor of five, and the limit on $\tau_{n-\bar{n}}$ will go up only by a factor of 2.4. The published Soudan-2 limit on τ_{nuc} yields $\tau_{n-\bar{n}} \gtrsim 2 \times 10^8$ sec., and the preliminary Super-K limit yields $\tau_{n-\bar{n}} \gtrsim 3 \times 10^8$ sec. The $\tau_{n-\bar{n}}$ reach of the planned experiments to search for proton decay is only about $\tau_{n-\bar{n}} \simeq 7 \times 10^8$ sec, which is far lower than the reach of $\tau_{n-\bar{n}} \simeq 10^{10} - 10^{11}$ sec anticipated for the free neutron search experiments being contemplated. Fig. 9 displays the current and future sensitivity of matter instability lifetime from $n - \bar{n}$ oscillations as well as from proton decay searches.
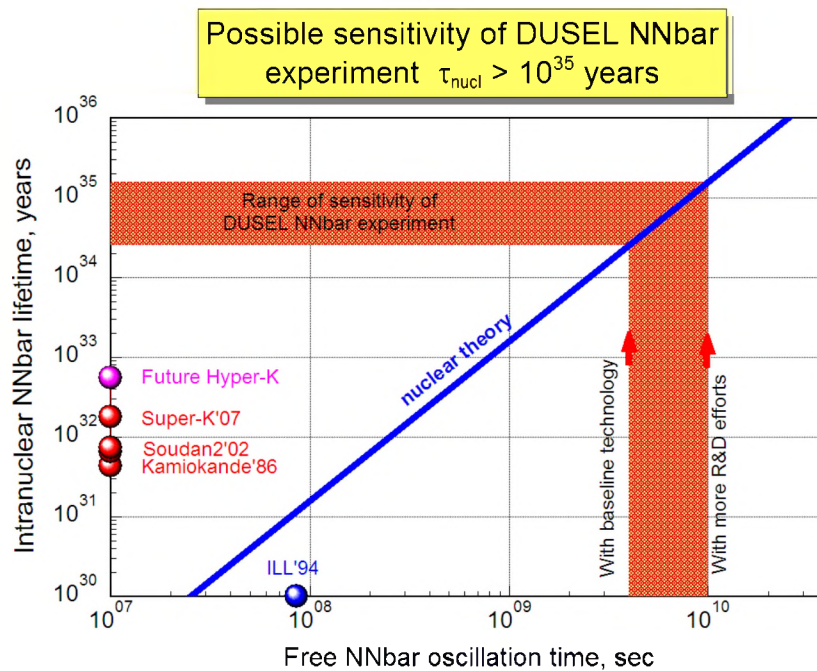

FIG. 9: Sensitivity of DUSEL NNbar experiment on matter instability lifetime.

What can we learn about the fundamental forces in nature and the working of the Universe from the $n - \bar{n}$ search?

Neutron-anti-neutron oscillations touch upon many areas of physics ranging from elementary particle physics to nuclear physics to astrophysics and cosmology. The potential of the search for

$n - \bar{n}$ oscillations as a probe of physics beyond the standard model is comparable to that of neutrino oscillations, which led to the very important discovery of neutrino masses and mixing. We now enumerate the most significant questions that will be addressed by an $n - \bar{n}$ oscillation search.

1. **Is the neutron its own anti-particle?**

   A search for $n - \bar{n}$ oscillations will probe new forces among particles at distance scales about a hundred times shorter than the ones that will be probed by the Large Hadron Collider (LHC). In specific models with low energy supersymmetry, the length scale of new physics probed in an $n - \bar{n}$ oscillation search can be one hundred million times shorter than the ones probed by the LHC. The discovery of neutrino masses is already providing one such probe of extremely tiny distances. Neutrinoless double beta decay experiments aim to test whether the neutrino is its own anti-particle, which is implied by many appealing theories explaining its small mass. If this is the case, then there are reasons to think that the neutron is its own anti–particle, a suggestion which goes back to the classic paper of Ettore Majorana in 1930's, since the neutrino and the neutron are linked by a symmetry of the standard model called B-L symmetry (see below) This gives greater motivation for the existence, at an observable level, of the phenomenon of $n - \bar{n}$ oscillation which is the experimental manifestation of the neutron being its own anti-particle.

2. **A new fundamental symmetry probed by $n - \bar{n}$ oscillations**

   To see which symmetry is probed in $n - \bar{n}$ oscillation searches, it is useful to compare with the situation involving neutrinos again. If the neutrino is its own antiparticle, this breaks total lepton number, L, by two units ($|\Delta L| = 2$). At an earlier time, most physicists believed that total lepton number was an exact symmetry, while at present, most physicists believe that it is broken. The process of neutrinoless double beta decay probes the scale of lepton number symmetry breaking. The standard model does not conserve L or B separately, but conserves their difference $B - L$. In a theoretical framework in which quarks and leptons are unified, one can get $|\Delta B| = 2$ processes. This happens, for example, in a class of unification models where the three colors of quarks combine with a lepton index to be part of a higher symmetry group $SU(4)$ which contains the familiar gauge force of strong interactions based on the color gauge group $SU(3)_c$. Such a framework automatically leads to the process of $n - \bar{n}$ oscillation without inducing proton decay. The scales of neutrino mass physics and of

$n - \bar{n}$ oscillations are then essentially the same, and the observation of the latter will provide important complementary information about the detailed nature of the physics of neutrino mass. There exist plausible models where this connection is clearly visible and where the $n - \bar{n}$ oscillation time is accessible to planned searches. For $n - \bar{n}$ oscillations to be observable, the scale of $B - L$ breaking must be in the 100 TeV range, which is fundamentally different from the popular approach based on grand unified theories (GUT's), where this breaking scale is around 10^{16} GeV. Thus, an observation of $n - \bar{n}$ oscillations would force us to fundamentally alter our thinking about unification of forces away from the conventional GUT approaches to partial unification at intermediate scales or possibly new physics at the TeV scale, such as TeV^{-1}-sized extra dimensions.

3. **$n - \bar{n}$ oscillation as a probe of extra dimensions**

There is currently a great deal of interest in the possibility that there may be extra hidden space-like dimensions in nature. Motivations for this arise from string theory, specifically in frameworks where the standard model fields themselves, in addition to gravity modes, propagate in these extra dimensions. One of the appeals of these models is that they can provide an explanation of the observed generational hierarchy in fermion masses; the differences in mass between various particles, e.g., up, down, and strange quarks, would be due to the fact that their chiral components are located at different sites in these extra dimensions. In such situations, it has been shown quantitatively that, while proton decay which involves quarks as well as leptons can be naturally suppressed, $n - \bar{n}$ oscillation, which involves only quarks, is generally unsuppressed, and can be in the observable range.

4. **Implications for cosmology**

The existence of $n - \bar{n}$ oscillations at an observable rate would also have profound implications for the origin of matter-antimatter asymmetry and thus the origin of a net excess of matter in the Universe. This is due to the fact that observable $n - \bar{n}$ oscillations would imply that process that violate baryon number would remain in equilibrium to very low temperatures, thereby erasing any matter-antimatter asymmetry generated in earlier epochs, as envisioned in currently popular scenarios such as leptogenesis. This would then require new ways to understand the origin of matter. Recently, such new mechanisms have been proposed, which can be independently tested at colliders. In these models, baryon asymmetry is induced after

the Universe undergoes the electroweak phase transition. Successful baryogenesis, in a class of models of this type, requires that $n - \bar{n}$ oscillations be observable, with $\tau_{n-\bar{n}} \sim 10^{10}$ sec.

5. Dark matter and connection with neutron–anti-neutron oscillations

There are some attractive models where neutron–anti-neutron oscillations also provide a probe of the nature of dark matter. A particularly intriguing suggestion is the possible existence of a parallel Universe with an identical duplicate of the observed matter and forces. Such a scenario could emerge from superstring theory. In that case, one expects all the particles that we know, protons, neutrons, etc., to have their mirror partners. Then the possibility arises that the neutron could oscillate into a mirror neutron. The same experiment that probes for $n - \bar{n}$ oscillations could also probe for such processes. Hydrogen atoms composed of mirror particles would serve as the dark matter of the Universe in this scenario. A possible connection between $n - \bar{n}$ oscillations and a dark matter candidate arises in models of low-scale baryogenesis which also have supersymmetry. The lightest stable superparticle in these models is not the neutralino, but the partner of the particle that generated the baryon asymmetry.

E.   Experimental Setup at DUSEL

DUSEL, with its Vertical Facility, can provide a unique opportunity to advance the search for $n - \bar{n}$ transitions by a sensitivity factor more than 1000 as compared with the present experimental limits. This sensitivity will be equivalent to reaching the lifetime for internuclear $n - \bar{n}$ transition of $\tau_{nuc} \sim 1 \times 10^{35}$ years. The major advantage of the vertical layout as compared with the alternative approach having a horizontal layout is the mitigation of the effect of the Earth's gravity on the motion of cold neutrons over the long flight length. In the baseline $n - \bar{n}$ experimental configuration, a 1-km long vertical shaft of 5-7 meters diameter would be equipped with a vacuum tube and Earth magnetic field compensation system. A 3.5 MW research reactor of TRIGA type operating in steady-state mode and installed on the top of the shaft would serve as the source of neutrons. Neutrons would be slowed down by a cryogenic liquid deuterium moderator to typical velocities below 1 km/s and dropped from the top of the vacuum tube through the focusing supermirror reflector system on an annihilation detector located at the bottom of the vertical tube. The background rate in the DUSEL $n - \bar{n}$ detector would be extremely low, allowing a single observed event to be a discovery. Active magnetic shielding of the flight tube would allow on/off switching

of the $n - \bar{n}$ transitions if the latter are observed. The proposed $n - \bar{n}$ experimental configuration is based on well-established technologies; the main challenge is in the engineering and vertical construction of the experiment. Further factors that can enhance the sensitivity of the vertical $n - \bar{n}$ search are a larger shaft length, larger reflection range of supermirrors (recently developed at KEK, Japan), development of a new "very cold" cryogenic moderator, and higher-power research reactor. After three years of running, $n - \overline{n}$ oscillation time sensitivity will improve by a factor of 1000 compared to the present sensitivity, with the possibility of improving by an additional factor of 4 in 12 years of running.

The 3.5 MW TRIGA reactor at the DUSEL Vertical Facility can be installed on the surface at the distance of about 2 km from the main underground experimental campus. The antineutrino flux produced by the reactor can be easily estimated as ~ 62 antineutrinos per kiloton-year (e.g. by rescaling from the KamLAND detector, where reactors with 120 GW thermal power at the average distance of 180 km produce ~ 263 antineutrino events per kiloton-year). This antineutrino flux certainly can be an essential background for geo-neutrino detection experiment at DUSEL, but, due to its controllable nature, it can be precisely measured. The flux of solar neutrinos to be coped with by the major experiments at the underground DUSEL site will be substantially larger than the flux of TRIGA antineutrinos. Given the large distance between the underground campus and the reactor, the background of thermal neutrons produced by the TRIGA reactor can be efficiently reduced to the level of environmental thermal neutron flux by simple passive shielding.