

DUSEL S1 Report on Large Detector for Long Baseline Physics, Nucleon Decay and Other Physics

Introduction

A large underground detector with an active mass greater than 100kT could become a key *shared physics research facility* for the future U.S. particle, nuclear and astrophysics research programs. A sensitive large detector with appropriate technical capabilities will address questions of fundamental importance, such as nucleon decay and matter-antimatter asymmetry amongst neutrinos. The detector will also serve as a facility for continuously observing natural sources of neutrinos and cosmic rays. All these tasks are active *simultaneously*.

This large multipurpose detector must have a mass in excess of 100kT to have significantly greater statistical reach to search for nucleon decay and to collect enough neutrino interaction events from accelerator-based neutrino beams with very long baselines to measure oscillation parameters with greater precision. For at least one of the favored proton decay modes (i.e. $p \rightarrow e^+ \pi^0$), the detector mass needs to approach 1 Mton for future progress. The detector needs to have a low energy threshold ($<5\text{MeV}$) and good energy resolution to detect supernovae and solar neutrinos. It should have good pattern recognition, timing and particle identification capability to distinguish electrons from muons and pions. To exploit the full scientific potential of such a detector, it will have to be located deep underground to shield it from cosmic ray background. Currently, only three technologies, water Cerenkov, liquid Argon time-projection, and liquid scintillator, have been proposed to meet these requirements and lead to affordable designs.

A recent U.S. Government policy document, "The Physics of the Universe"¹, considers the science and technology that would be provided by such a detector and concludes that it has high scientific value and is also judged to be "Ready for Immediate Investment and Direction Known" (Page 5). To bring this policy position to practical application, a near-term program of research and development is needed to decide on the appropriate detector technologies, perform engineering design studies related to credible sites for such a detector, and determine the cost and schedule for such a detector. Since the long baseline oscillation experiment is a crucial aspect of this facility, the program to develop the appropriate neutrino beam must be resolved.

Scientific Scope of the large detector in DUSEL:

A large multipurpose detector can simultaneously address three broad physics research topics:

- 1) Neutrino oscillations with a very long baseline and accelerator-produced super neutrino beam;
- 2) An improved search for nucleon decay;

- 3) Detection and study of neutrinos from natural sources such as the Sun, Earth's atmosphere, past or current supernova explosions plus, as yet unsuspected new sources of neutrinos.

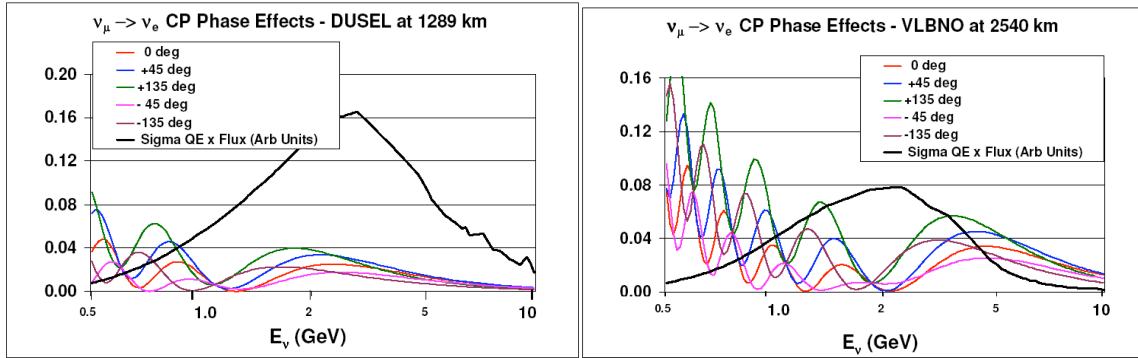
We briefly summarize the physics research topics below.

Physics Topic 1 – Neutrino Measurements Using Accelerator Produced Beams

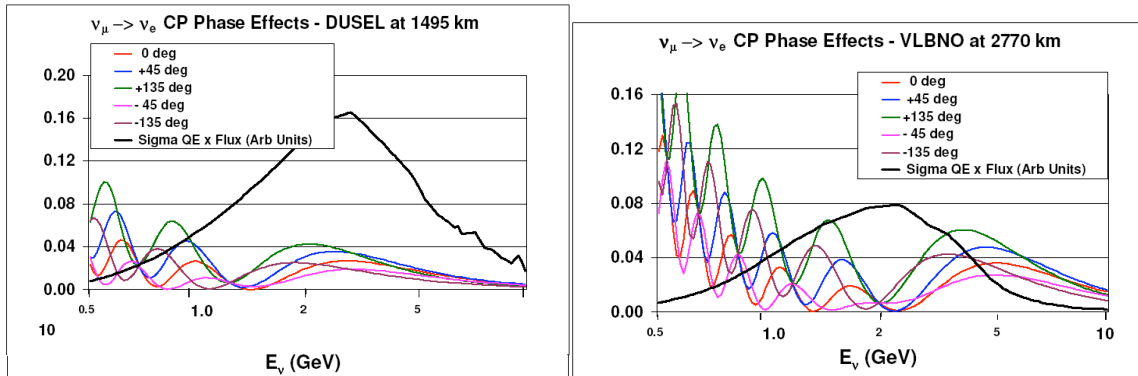
In references^{4,5,6}, as well as additional references contained therein, it has been argued that an intense, accelerator-generated, broad-band muon neutrino beam, coupled with a large experimental detector located more than 1000 km away from the beam source, could be used to perform precision measurements of neutrino oscillation properties such as the mass differences, the mass hierarchy, the mixing parameters, and CP-violation in the neutrino sector. Using currently known values for the neutrino mass differences and mixing parameters⁷, several rules of thumb have been formulated to characterize such an experiment:

- 1) It is desirable to observe a pattern of *multiple nodes in the energy spectrum* of muon neutrino disappearance and electron neutrino appearance. Such a pattern of oscillations is important for extraction of signal from background as well as the precision measurements of parameters. Since the cross section, Fermi motion and nuclear effects limit the resolution of muon neutrino interactions below ~ 1 GeV, a wide-band muon neutrino beam with energy range of 1-6 GeV and a distance of ~ 2000 km is needed to observe 3 or more oscillation nodes.
- 2) The *appearance spectrum of electron neutrinos* from the oscillation of ν_μ to ν_e contains information about $\sin^2 2\theta_{13}$, δ_{CP} , Δm_{21}^2 and the ordering of neutrino masses through the matter effect. One of the key unknowns in neutrino physics is whether the mass ordering of neutrinos is “normal”, resembling the ordering of quark and charged lepton masses ($m_1 < m_2 < m_3$), or “reversed”, in which the masses of states associated with electrons and muons are heaviest ($m_3 < m_1 < m_2$). It was shown in our references that the various parameters can be separated out and measured using only *a single detector* in the broad-band 1-6 GeV beam with the >1000 km baseline. In such an experiment successive oscillation nodes have different dependence on the parameters and therefore can lead to a robust measurement.
- 3) For normal mass ordering, the matter effect causes the conversion probability to increase with energy and is most pronounced at energies >3 GeV. In contrast the effects of δ_{CP} fall as $1/E$. Our references show that this energy dependence can be used to measure the value of δ_{CP} and $\sin^2 2\theta_{13}$ without requiring anti-neutrino data for the case of normal mass ordering. Neutrino and anti-neutrino data together, will be needed to cover both possibilities of the mass ordering, and will lead to definitive result on CP-violation and precision measurement of the CP parameter δ_{CP} . The energy dependence becomes larger for longer baseline distances and it is therefore advantageous to perform the experiment with a *very long (1000 to 3000 km) baseline*, because we can then relax the requirements on systematic errors for the flux, the cross-sections, the other oscillation parameters, and for calculation of the matter effect.

In Figs. 1a, 1b, 1c and 1d we illustrate the neutrino oscillation behavior and its dependence on baseline distance. In these graphs, we see the *appearance of electron neutrinos* from an initial beam of muon neutrinos as predicted by already-measured neutrino mass differences using an approximate formula that includes matter effects⁴. The figures are plotted for the case of perfect energy resolution and no background, ideal for illustrating the basic physics behavior. Also plotted is a practical wide-band neutrino flux spectrum, weighted by neutrino energy, able to be generated by a multi-GeV proton accelerator (BNL and Fermilab are depicted). These curves show the relative event yields as a function of neutrino energy, that could be expected in actual experiments, because the total neutrino cross section in this energy regime is proportional to energy.



Figs. 1a, 1b – CP-violation phase behavior for broad-band neutrino beams from BNL and Fermilab to the Homestake Mine in Lead, South Dakota, a potential DUSEL site.



Figs. 1c, 1d – CP-violation phase behavior for broad-band neutrino beams from BNL and Fermilab to the Henderson Mine in Colorado, a potential DUSEL site.

Note that multiple nodes can be observed in both ν_e spectra and that different values of the CP-violation phase, δ_{CP}, are unambiguously distinguishable over this neutrino energy range in both examples with these baselines. This is an experimental feature that is unique to the very long baseline method using a broad-band beam.

Physics Topic 2 – Improved Search for Nucleon Decay

Theoretical Motivation

While current experiments show that the proton lifetime exceeds about 10^{33} years, its ultimate stability has been questioned since the early 1970's in the context of theoretical attempts to arrive at a unified picture of the fundamental particles – the quarks and leptons – and of their three forces: the strong, electromagnetic and weak. These attempts of unification, commonly referred to as “Grand Unification”, have turned out to be supported empirically by the dramatic meeting of the strengths of the three forces, that is found to occur at high energies in the context of so-called “Supersymmetry”, as well as by the magnitude of neutrino masses that is suggested by the discovery of atmospheric and solar neutrino oscillations. One of the most crucial and generic predictions of grand unification, however, is that the proton must ultimately decay into leptonic matter such as a positron and a meson, revealing quark-lepton unity.

Certain early versions of grand unification based on the so-called SU(5) and minimal supersymmetric SU(5) models predict relatively short lifetimes for the proton ranging from 10^{28} to 10^{32} years, in the $e^+\pi^0$ and μ^+K^+ respectively. These predictions have been excluded by the IMB/Kamiokande and Super-Kamiokande experiments. A class of well-motivated theories of grand unification, based on the symmetry of SO(10) and Supersymmetry, which have the virtue that they successfully describe the masses and mixings of all quarks and leptons including neutrinos, and which also explain the origin of the excess of matter over anti-matter through a process called “leptogenesis”, provide a conservative (theoretical) upper limit on the proton lifetime which is within a factor of ten of the current lower limit. This makes the discovery potential for proton decay in a next-generation rather high.

From a broader viewpoint, proton decay, if found, would provide us with a unique window to view physics at truly short distances – less than 10^{-30} cm., corresponding to energies greater than 10^{16} GeV – a feature that cannot be achieved by any other means. It would provide the missing link of grand unification. Last, but not least, it would help ascertain our ideas about the origin of an excess of matter over anti-matter that is crucial to the origin of life itself. In this sense, and given that the predictions of a well-motivated class of grand unified theories for proton lifetime are not far above the current limit, the need for an improved search for proton decay through a next-generation detector seems compelling. The theoretical guidance provided by a class of promising models, including those based on Supersymmetric SO(10), flipped SU(5) and string-derived SU(2) \times SU(2) \times SU(4) symmetries, points especially towards the need for improved searches for proton decaying into μ^+K^+ and $e^+\pi^0$ modes with lifetimes less than about 2×10^{34} and 10^{35} years respectively. Should proton decay be discovered in these modes, valuable insight would be gained by searches for other related modes including $\mu^+\pi^0$ and μ^+K^0 .

Current status of experimentation

The “classical” proton decay mode, $p \rightarrow e^+\pi^0$, can be efficiently detected with low background. At present, the best limit on this mode ($\tau/p > 5.4 \times 10^{33}$ yr, 90% CL) comes from a 92 kton-yr exposure of Super-Kamiokande. The detection efficiency of 44% is dominated by final-state π^0 absorption or charge-exchange in the nucleus, and the expected background is 2.2 events/Mton-yr.

The mode $p \rightarrow \pi K^+$, is experimentally more difficult in water Cherenkov detectors due to the unobservable neutrino and the fact that the kaon is below Cherenkov threshold. The present limit from Super-Kamiokande is the result of combining several channels, the most sensitive of which is $K^+ \rightarrow \mu^+ \nu$ accompanied by a de-excitation signature from the remnant ^{15}N nucleus. Monte Carlo studies suggest that this mode should remain background free for the foreseeable future. The present limit on this mode is $\tau/p > 2.2 \times 10^{33}$ yr (90% CL).

Requirements for the next decade

Since the lifetime of the nucleon is unknown, *a priori* (if one were to ignore theoretical guidance), and could range from just above present limits to many orders of magnitude greater, progress in this search must be measured logarithmically: increases in sensitivity by factors of a few are insufficient to motivate new experiments. Thus, continued progress in the search for nucleon decay inevitably requires much larger detectors. The efficiency for detection of the $e^+ \pi^0$ mode is dominated by pion absorption effects in the nucleus, and cannot be improved significantly. An order of magnitude improvement in this mode can only be achieved by running Super-Kamiokande for an additional 30-40 more years, or by constructing an order of magnitude larger experiment.

The decay modes of the nucleon are also unknown, *a priori*, and produce quite different experimental signatures, so future detectors must be sensitive to most or all of the kinematically allowed channels. Moreover, the enormous mass and exposure required to improve significantly on existing limits (and the unknowable prospects for positive detection) underline the importance of any future experiment's ability to address other important physics questions while waiting for the proton to decay. Proton decay experiments have made fundamental contributions to neutrino physics and particle astrophysics in the past, and any future experiment must be prepared to do the same.

New facilities under consideration

A variety of technologies for discovery of nucleon decay have been discussed. Of these, water Cherenkov appears to be the only one capable of reaching lifetimes of 10^{35} years or greater. Cooperative, parallel studies of a future underground water Cherenkov proton decay experiment are underway in the U.S. and Japan. The proposed designs have fiducial volumes which are about 20-25 times the Super-Kamiokande fiducial volume.

Other techniques, for instance liquid Argon or scintillation, have been discussed and may have significant efficiency advantages for certain modes that are dominant in a certain broad class of SUSY theories. Liquid Argon time projection chambers potentially offer very detailed measurements of particle physics events with superb resolution and particle identification. Liquid Argon feasibility will be demonstrated in the near future with the operation of a 600-ton ICARUS detector. If expectations are correct, it should have a sensitivity that is equivalent to a 6000-ton water Cherenkov detector in the $p \rightarrow \pi K^+$ mode. The liquid scintillator approach is presently being explored with the 1kt KamLAND experiment. It should also have enhanced sensitivity to this mode by directly observing the K^+ by dE/dx and observing the subsequent $K^+ \rightarrow \mu^+ \nu$ decay.

The advantage of a water Cherenkov detector is that it is a proven technology that has

been perfected over several decades. Water Cherenkov detectors are in operation in Japan (Super Kamiokande with a total mass of ~ 50 kT) and in Canada (the Sudbury Neutrino Observatory, SNO, with 1 kT of D_2O and 5 kT of H_2O). The largest liquid scintillator detector in operation today is Kamland in Japan with 1.2 kT of liquid scintillator in its fiducial volume.

A program of R&D to further develop these technologies and to make a well considered choice among them is especially appropriate at this time.

Performance and feasibility

Detailed Monte Carlo studies, including full reconstruction of simulated data, indicate that the water detectors could reach the goal of an order of magnitude improvement on anticipated nucleon decay limits from Super-Kamiokande. With sufficient exposure, clear discovery of nucleon decay into $e^+\pi^0$ would be possible even at lifetimes of $(\text{few}) \times 10^{35}$ years where present analyses would be background-limited, by tightening the selection criteria. For instance, with a detection efficiency of 18%, the expected background is only 0.15 events/Mton-yr, ensuring a signal:noise of 4:1 even for a proton lifetime of 10^{35} years. A water Cherenkov detector would also provide a decisive test of super-symmetric SO(10) grand unified theory by reaching a sensitivity of a $(\text{few}) \times 10^{34}$ years for the $\pi^+ K^+$ mode.

As we have discussed, a much smaller liquid argon could do particularly well on the mode νK^+ as the efficiency could be as much as 10 times larger than that in the water Cherenkov detectors due to the extraordinary bubble chamber-like pattern recognition capabilities. Due to this, a single observed event could be powerful evidence for a discovery. The $e^+\pi^0$ mode however would be limited by the smaller size of these detectors.

A detector with mass O(1 Mton) would also be a powerful tool for studying neutrino physics. Thanks to the larger dimensions of the detector, higher energy neutrino-induced muons can be fully contained and their energy can be measured. Using the atmospheric neutrino flux, the distinctive oscillatory pattern as a function of L/E could be directly observed. Thus, as discussed earlier, a large proton decay detector would also be the ideal distant detector for a long-baseline oscillation experiment; several studies indicate sensitivity to $\sin^2 2\theta_{13}$ at about the 10^{-3} level, and sensitivity to leptonic CP violation. R&D towards more efficient and economical photo-detection – both improved conventional photo-multiplier tubes and more novel technologies – while not required to build the next large detector, could reduce its cost and increase its physics reach considerably. This R&D should be strongly supported, since they will also benefit a host of other research efforts.

The search for n - \bar{n} oscillation is another test of baryon non-conservation. While this is not one of the favorite predictions of conventional SUSY grand unification, this process, taking place in the nuclear potential, can reach an equivalent sensitivity to baryon non-conservation of 10^{35} years. Experiments have been proposed which could give a factor of 10^3 improvement in the current limits.

Depth requirements

Most of the decay modes that were searched for in the first generation detectors required

only modest depth. IMB operated successfully at a depth of 2000 feet. The proposed ultimate DUSEL depth (about 6500 mwe) would reduce the muon background by about a factor of 100 with respect to Super-K and certainly help in the observation of modes with a low energy component or those influenced by fast neutron background. As an example of this, the mode $n \rightarrow p + e + \bar{\nu}_e$ can be searched for by observing the de-excitation of the residual nucleus. This is difficult with a background of fast-neutron induced low energy background events.

Physics Topic 3 – Observation of Natural Sources of Neutrinos

All of the detector technologies we consider will lead to enhanced detection and study of neutrinos from natural sources such as the Sun, Earth's atmosphere and lithosphere, and past and current supernova explosions. There may also be previously unsuspected, natural neutrino sources that appear when the detector mass reaches the hundreds of kilotons scale. The liquid scintillator technique is of particular note here because it could allow the detection of low energy antineutrinos from Earth's lithosphere.

Solar neutrinos have already been observed in the Super Kamiokande¹⁰ and SNO detectors¹¹. If the large detector concepts discussed here result in construction of the underground experiment, it may become possible to increase the observable event rate enough to clearly observe spectral distortion in the 5 to 14 MeV region. One could also measure the as yet undetected hep solar neutrinos (with end point of 18.8 MeV) well beyond the ⁸B endpoint (~14 MeV). These measurements would require a very comprehensive understanding of the detector systematics and energy resolution, but a better determination of the solar spectrum as well as detection of the day-night effect with high statistics would represent a significant advance in the evolution of solar nuclear physics measurements.

The observation of supernova neutrino events in a large neutrino detector of the type being discussed in this proposal is straightforward and has historical precedent. The SN 1987A supernova, in fact, was seen by *two* large water Cerenkov detectors (11 events in Kamikande-II (total mass~3kT) and 8 events in IMB (total mass~7kT)) that were active in proton decay searches at that time¹². The predicted occurrence rate for neutrino-observable supernovae (from our own galaxy and of order 10 kpc distant) is about 1 per 20 years, so events will be very rare¹⁵. However, the information from a single event, incorporating measured energies and time sequence for tens of thousands of neutrino interactions, obtained by a very large neutrino detector, could provide significantly more information than has ever been obtained before about the time evolution of a supernova. In addition to obtaining information about supernova processes, the small numbers of SN1987a neutrino events have been extensively used to limit fundamental neutrino properties. Supernova processes continue to have very high interest because of the recent detection of the acceleration of the rate of expansion of the universe using type Ia supernova. Recent work has shown that diffuse neutrino events from past core collapse supernova (which produce neutrino bursts) could be used in to gain independent knowledge on the cosmological evolution parameters¹³. Therefore we regard detection of supernova neutrinos, either as a burst from a single supernova and as

a diffuse source from past supernovas, a key mission of the multipurpose detector facility at DUSEL.

With some 20-100 times the sensitive mass and, hopefully, a lower neutrino energy threshold (a few MeV), the energy and arrival-time spectra would have statistical power that the earlier detectors could not provide. The uncertainty of obtaining a supernova event may make this research topic insufficient to motivate construction of its own detector. But when this topic is added to the mission of a multipurpose detector, the increased science potential at virtually no additional cost to the integrated program is very compelling.

The continued study of atmospheric and solar neutrinos in the large underground detector will provide useful additions to the program carried out so successfully by the Super-Kamiokande Experiment. The factor of 20 increase in detector fiducial mass will allow statistical improvements in all the topics studied and, perhaps, the emergence of new scientific topics. Statistical clarification of the day-night effect for solar neutrinos is one topic that will benefit from the strongly improved statistics. Other natural sources of neutrinos, such as relic supernova and lithospheric neutrinos, have not yet been studied extensively and could, in principle, be observed by the new detector concepts. An initial result in this area has recently been announced by KamLAND¹⁴. Typically, the neutrino energies for these processes are below 10 MeV and are sensitively dependent upon the low-energy threshold capability of the new detectors. The liquid scintillator detector concepts are likely to have the best opportunities for advancing these topics, but liquid argon detectors could also contribute.

Finally, we note that there may be galactic sources of neutrinos that are of lower energy and greater abundance than the ultra high-energy neutrino sources to be explored by detectors such as the 'Ice Cube' Cerenkov detector now being constructed deep under the Antarctic ice sheet by an NSF sponsored collaboration. Galactic neutrinos have a natural source in inelastic nuclear collisions through the leptonic decays of charged secondary pions. This source is expected to be of comparable intensity and energy distribution to the high-energy photons that are born from neutral pion decays in the same collisions¹⁵. Such neutrino sources, currently not detectable with Super-Kamiokande, could be seen by a megaton-class neutrino detector that runs for several decades. Such a scientific scenario is consistent with the DUSEL scientific mission.

Relationship of the Physics Topics to the DUSEL Project

A large detector facility located in the DUSEL is the optimum way to pursue all three of the above physics research goals. The important technical capabilities for such a detector are its fiducial mass, energy threshold, energy resolution, muon/electron discrimination, pattern recognition capability, time resolution, low-radioactivity detector environment, and depth of the underground site of the detector. The capital and operating costs for the detector are also a serious concern. The fiducial mass requirement derives from the precision sought for the CP-violation measurement

(assuming that the value of $\sin^2 2\theta_{13} > 0.01$) and from the sensitive target mass needed to detect nucleon decay. A measurement uncertainty of ~ 10 - 20 deg. on the CP phase angle will require a detector in excess of 100 kT (regardless of the length of the baseline), since current technology limits the proton beam power to less than about 2 MW. For nucleon decay, it is clear that improvements in the sensitivity of the Super-Kamiokande detector, either a detector with much greater fiducial mass, or with much better efficiency for certain modes, (or both) is needed to advance this field. The efficiency can be improved by employing more advanced detection techniques for some of the limited set of potential nucleon decay modes currently targeted. Therefore, a very large detector that is able to combine the measurement of accelerator-based neutrino oscillation parameters with a sensitive new search for nucleon decay presents a very compelling component for the DUSEL science mission.

For the neutrino oscillation physics that we propose here, we noted that it is important to obtain good energy resolution on the neutrino energy, excellent pattern recognition, and a low energy threshold. The required energy resolution can be achieved by separating quasi-elastic scattering events, with well-identified leptons in the final state, from the inelastic charged-current and neutral-current events. If a very fine-grained detector (such as liquid argon TPC) is used, it might be possible to use all of the charged current events and still obtain adequate energy resolution. One of the key questions that is under intense study is how well quasi-elastic events for muon and electron neutrinos can be separated from other background events. A second important question is what statistical gain can be realized if a fine-grained detector uses a larger fraction of the charged current events. We also note that the absolute energy scale calibration in the detector is important and will require careful study to provide the lowest systematic error with a practical calibration system. Obtaining definitive answers to these detector performance questions constitutes an important goal of the event simulation and event reconstruction software R&D.

Lastly, the energy threshold and the depth of the detector will determine the low-energy and low-rate capability of the detector for the detection of solar, and supernova neutrinos, as well as detection of atmospheric neutrinos, lithospheric anti-neutrinos and diffuse relic neutrinos from long past supernovae. The DUSEL is expected to provide sufficient depth for these purposes, however, a detailed study of the trade-offs in depth versus physics capability is needed for each of the technologies considered.

¹ “The Physics of the Universe, a Strategic Plan for Federal Research at the Intersection of Physics and Astronomy”, National Science and Technology Council Committee on Science, February 2004, <http://www.ostp.gov/html/physicsoftheuniverse2.pdf>; also, “FY 2007 Administration Research and Development Budget Priorities”, J.H. Marburger, III and J.B. Bolten, Executive Office of the President Memorandum, July 8, 2005, http://www.ostp.gov/html/budget/2007/ostp_omb_guidancememo_FY07.pdf.

² DUSEL announcement,

http://www.nsf.gov/news/news_summ.jsp?cntn_id=104313&org=MPS&from=news

³ “Neutrinos and Beyond – New Windows on Nature”, National Research Council Study, National Academies Press, 2003.

⁴ M. Diwan et al., *Phys. Rev. D.* 68, 012002 (2003).

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- ⁶ W. Marciano, "Extra Long Baseline Neutrino Oscillations and CP Violation", arXiv:hep-ph/0108181 v1, 2001.
- ⁷ A. Strumia & F. Vissani, hep-ph/0503246 IFUP-TH-2005-06, Mar 2005.
- ⁸ UNO EOI, <http://nngroup.physics.sunysb.edu/uno/publications.shtml>; C. K. Jung, "Feasibility of a Next Generation Underground Water Cherenkov Detector: UNO", [hep-ex/0005046], NNN99 Proceedings.
- ⁹ LAr Detector homepage, <http://www.aquila.infn.it/icarus/exp.html>
- ¹⁰ Super Kamiokande detector homepage, http://www-sk.icrr.u-tokyo.ac.jp/sk/index_e.html
- ¹¹ SNO detector homepage, <http://www.sno.phy.queensu.ca/>
- ¹² C.B. Bratton et al., *Phys. Rev.* **D 37**, 3361 (1988); K. Hirata et al., *Phys. Rev.* **D 38**, 448 (1988)
- ¹³ Probing Dark Energy via Neutrino & Supernova Observatories. Lawrence J. Hall, Hitoshi Murayama, Michele Papucci, Gilad Perez (LBL, Berkeley & UC, Berkeley) . e-Print Archive: **hep-ph/0607109**
- ¹⁴ T. Araki, et al., *Nature* Vol 436, No. 7050 (2005) p499.
- ¹⁵ M.L. Constantini and F. Vissani, e-Print Archive: astro-ph/0508152