Appendix E: Supplementary Science Book Physics

A plan for physics in the next decade in DUSEL has been developed with a portfolio of specific science directions in several recent physics and astronomy surveys including:

1. the ongoing NSF S1 Solicitation process (http://www.dusel.org)
2. the APS Study on Neutrino Physics (2004) (http://www.aps.org/neutrino/)
3. the National Research Council Report of the Neutrino Facilities Assessment Committee (2003) (http://books.nap.edu/catalog/10583.html)
4. the National Research Council Report on "Connecting Quarks with the Cosmos" (2002) (http://books.nap.edu/catalog/10079.html)

The Kimballton team of physicists has actively contributed to the above reports, particularly the S1 process and the APS study. Their experience in this science is based on participation in and development of the concepts and the science and technology of almost every major underground experiment world-wide.

The S1 process has identified an array of frontier physics/astrophysics questions such as:

- search for proton decay
- CP violation in the neutrino sector probed by long baseline high energy neutrinos
- the fundamental nature of neutrinos (Majorana/Dirac) probed uniquely via double beta decay
- the precise formulation of the neutrino mass/mixing matrix using neutrino beams from terrestrial devices and the sun
- real-time spectroscopy of proton-proton solar neutrinos and measurement of the neutrino luminosity of the sun
- probing the nature of dark matter in the Universe
- interior structure of the earth probed by antineutrino emission from U and Th and other sources inside the earth
- detailed astrophysics of stellar explosions via neutrino observations
- observation of supernova relic neutrinos.

Typical experiments called out in the S1 process that address these questions fall into broad classes of size of detectors/experiments, technology and optimum depth. Solar neutrino detectors are of medium size (100-1000 tons), using a variety of conventional and cryogenic technologies and they require depths of 2000-4500 mwe. Double beta decay experiments, as well as dark matter detectors, are relatively small (<1 ton), use a variety of detection technologies, (particularly those based on cryogenics) and need a deep site (>6000 mwe). All the other topics above need very large (100 kilotons -1 megaton) devices based on water Cerenkov, liquid scintillation or liquid argon technologies operating at moderate depths (~4000 mwe). The open nature of the questions and the high cost of experiments such as the large scintillation and Cerenkov detectors stress designs that permit multi-science functions. They are thus designed to be sensitive to long baseline detection of high energy neutrinos from terrestrial accelerators situated at optimal distances and for proton decay searches, geophysics and supernova astrophysics and cosmology. The Kimballton-DUSEL laboratory is being designed to accommodate any of the physics experiments envisioned in the S1 infrastructure matrices.

In addition to the broad requirements listed above, there are specialized requirements for particular experiments - low radon background from surrounding rock, adequate clean facilities, and capability for handling large volumes of cryogens. The existing Kimballton mine already has stable, old caverns up to 15 x 30 x 100 m in size at a depth of 1700-2300 mwe that have adequate electrical services. Experiments can already be accommodated in such caverns—e.g., a pp-neutrino sensitive solar neutrino detector (such as LENS, see below). Our conceptual design plan will include a main laboratory at 4500 mwe depth that will provide facilities for the typically large multifunctional experiments (such as HSD, see below). A deep laboratory at 7500 mwe depth will potentially house experiments up to 15x15 x 15m, e.g., dark matter and double beta decay experiments (see S1 report).

The planning of the DUSEL-Kimballton laboratory will accommodate an initial suite of experiments under the guidance of the S1 process and a Kimballton Science Advisory Committee from a slate of experiments identified by normal review processes. The likely requirements in the longer-- 30 year-- outlook will depend on what we learn from experiments in the short term. Future experiments will likely require even larger detectors than those presently discussed. A conscious effort will be made in the design layouts to allow for expansion of the facilities for future science.

The Kimballton-DUSEL physics team has been actively developing specific physics experimental projects for some time, independent of the DUSEL developments. The physics questions addressed in these projects cover almost every topic in the S1 list above. The team is especially excited and enthusiastic about Kimballton-DUSEL because it brings an attractive new dimension to these plans by the proximity of the mine to several home laboratories of the team. This important aspect will obviously enhance intellectual and technological activity in a variety of tangible and intangible ways. Some of the projects of interest are described below.

Double-Beta Decay to Excited States

(TUNL, Duke U)

In order to extract a value for the neutrino mass from zero-neutrino double-beta decay ($0\nu 2\beta$) data, information on nuclear matrix elements (NMEs) is required. There is an important distinction between theoretical models used to predict nuclear matrix elements for double-beta decay ($2\nu2\beta$) transitions to the ground state and those that estimate NMEs for transitions to excited final states. The ground-state matrix elements are, in general, functions of the proton-neutron particle-particle strength parameter g_{pp}. The strong dependence on g_{pp} grants a large amount of freedom to a given model in choosing an appropriate value of g_{pp} in such a way that the model's predictions for decay half-lives conform to experimentally measured half-lives. On the other hand, 2β transitions to excited final states involve NMEs that are much less sensitive to g_{pp}. Therefore, a measurement of the half-life of the $2\nu2\beta$ decay to an excited 0^+ final state constitutes a more severe test of theoretical models, while at the same time making these transitions easier to predict.

Recently, it was proposed that the Pauli exclusion principle may be violated for neutrinos, and consequently, neutrinos obey at least partly the Bose-Einstein statistics. Bosonic neutrinos may form the cosmological Bose condensate which may account for all (or part of) the dark matter in the universe. The "wrong" statistics of neutrino has far reaching consequences. The possible violation of the Pauli principle for neutrinos can be tested in the $2\nu2\beta$ decay. One of the most sensitive tests is the ratio of the transitions to the excited 0^+ state and the ground state.

The ground state $2\nu2\beta$ transition rate has been measured very well for ^{100}Mo. At Kimballton-DUSEL we plan to improve the measurements for the half-life of the transition to the excited 0^+ state by detecting the 539.5 keV and 590.8 keV gamma rays in coincidence (see Fig.1). Currently, such an experiment is being performed on ground level in the basement of the Duke Physics Department. A move of the existing apparatus (Fig.2) to Kimballton will greatly improve the background observed in the present measurements, resulting in a much improved determination of the present value

$$T_{1/2}(0\nu + 2\nu) = [\,5.0\ ^{+1.0}_{-0.7}\ (\text{stat}) \pm 0.5\ (\text{syst})] \times 10^{20}\ \text{years}.$$

Due to the coincidence requirement a large depth is not required in order to reduce the cosmic-ray induced background to the required level. Therefore, even the existing caverns at the Kimballton mine are ideal for this type of experiment.

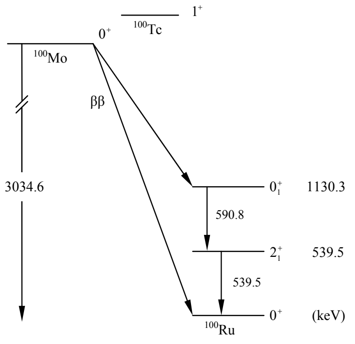


Figure 1. Level scheme of ^{100}Mo double-beta decay.

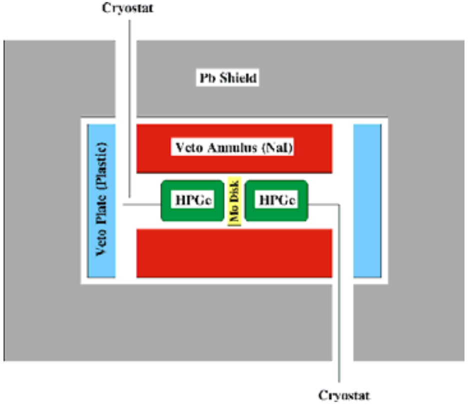


Figure 2. Double-beta decay apparatus consisting of two HPGe detectors with Mo-disk, NaI annulus and plastic scintillators (active cosmic-ray veto) and Pb shielding.

Astrophysical Nuclear Reaction Studies Underground

(A. Champagne (UNC), Jeff Blackmon (ORNL)

Stars spend most of their lives producing energy quiescently through a series of rather well defined stages of nuclear burning. The ashes left behind are what cause stars to evolve and thus nucleosynthesis is a key ingredient in studies of stellar structure and evolution. Measurements of nuclear reactions are combined with stellar models to interpret observations of elemental and isotopic abundances in stars, the interstellar medium, meteorites, etc., which then provides information about the inner workings of stars that is not directly accessible. This work has implications beyond the scope of stellar astrophysics. For example, one way to study the evolution of galaxies is through analyses of stellar populations. Stars can provide information about the timescale for formation of structure in the universe. The latter stages of stellar evolution can be used as a laboratory for fundamental physics. All of this is ultimately based on some understanding of stellar evolution. The improving precision and sensitivity of these observations have revealed very detailed information about stellar interiors and a number of surprises, and represents a major challenge to nuclear physics. The cross sections of interest are incredibly small and experimental sensitivity is severely limited by cosmic-ray induced backgrounds. An underground laboratory therefore provides an ideal environment for low-energy accelerators designed to measure nuclear astrophysics cross sections.

Every reaction to be measured presents unique technical challenges and no single approach is guaranteed to work in every case. Therefore, an underground accelerator facility must be flexible in the beams and energies that it provides. For this reason, we envision 2 separate, complementary facilities. The first would be a high-current (10 mA pulsed), low-energy (< 300 keV) proton accelerator. This is intended for measurements where the physics demands very low bombarding energies and where beam-induced backgrounds are not a limitation. The second facility would be a heavy-ion accelerator, capable of producing beams of up to 0.2 mA with energies of up to 6 MeV, for measurements in inverse kinematics (for example, shown in Fig. 3). This accelerator would be coupled to a high-efficiency recoil separator. This system would be used for measurements where a clean tag on the residual nucleus is required to improve sensitivity. Both accelerators would be instrumented with a suite of detector and target systems that could be configured to suit the needs of a particular measurement. The laboratory would be located at a depth of at least 3,000 mwe and would occupy a volume of 15 x 20 x 5 m^3 (L x W x H).

Fig 3 One possibility for a heavy-ion accelerator is a single-ended Dynamitron similar to that shown here.

LENS-Sol

[Hahn, Min-fang Yeh, Garnov (BNL), Benziger (Princeton U), Champagne (UNC), Galindo-Urribari, Blackmon, Gomez (ORNL), Barabanov, Gurentsov, Kornoukhov, Bezrukov (INR Moscowa) Gavrin, Abdurashitov, Kopylov (INR Troitsk); Raghavan, Vogelaar, Pitt, Grieb, Zhang Chang (VT)]

The aim of LENS-Sol is to directly observe the low energy (<2 MeV) spectrum of solar neutrinos including those from the basic pp-fusion in the sun and thereby make a precision measurement of the neutrino luminosity of the sun. The result impacts with high discovery potential on topics in particle physics [neutrino phenomenology (tests and improved precision of the neutrino-mass mixing structure, neutrino magnetic moment), non-standard interactions in particle physics, CPT invariance] as well as solar astrophysics (precision tests of solar models including search for hidden sources of energy other than fusion reactions in the sun). While LENS-Sol operates via CC-based neutrino detection (only electron-flavor) other pp-neutrino sensitive experiments have been proposed [CLEAN (http://mckinseygroup.physics.yale.edu/clean/) , HERON (http://www.physics.brown.edu/physics/researchpages/cme/heron/LTD_home.html)] based on electron-scattering.

The LENS-Sol experiment is based on the neutrino capture reaction with the element indium (with 96% of the isotope A=115) that presents a low threshold of only 114 keV for the capture. The reaction is favorable because it yields: 1) the incident neutrino spectrum directly with the spectrum of the electrons emitted following neutrino capture since $E_e = E_\nu$ -114 keV; 2) The low threshold enables observation of the pp neutrinos (0-420 keV); 3) the capture reaction supplies a unique tag of the neutrino capture reaction via the delayed coincidence of a cascade of two gammas that follow neutrino capture. The experimental spectrum observable in this reaction is shown in Figure 4.

The major background arises from the natural radioactivity of indium via emission of bet-rays with a maximum energy of 500 keV. In particular, bremsstrahlung (BS) of these betas can seriously mimic the neutrino capture tag The problem of suppressing this background has recently been solved via two major breakthroughs: 1) the development of a high-quality In-loaded liquid that combines a). sizable In loading ~8%; b) high scintillation efficiency (40-60% of the solvent light efficiency; c) very long light transmission lengths ~8m; and d) chemical and optical stability over periods ~1 year and 2) Analysis strategies that effectively exploit the assets of the liquid scintillator above. The experimental arrangement envisages an In mass of ~20 tons and scintillator mass of some 300-400 tons. The experiment can be performed at relatively moderate depths of ~2000 mwe without interference from cosmogenic backgrounds.

The detector is modular, based on an array of longitudinal modules. A conceptual design achieves this design in a tank of the scintillator that contains a cage of light pipes (see Figure 5) The optical segmentation is made via multilayer foils that pipe light via both total internal reflection and specular reflection to photomultipliers at either end of the tank.

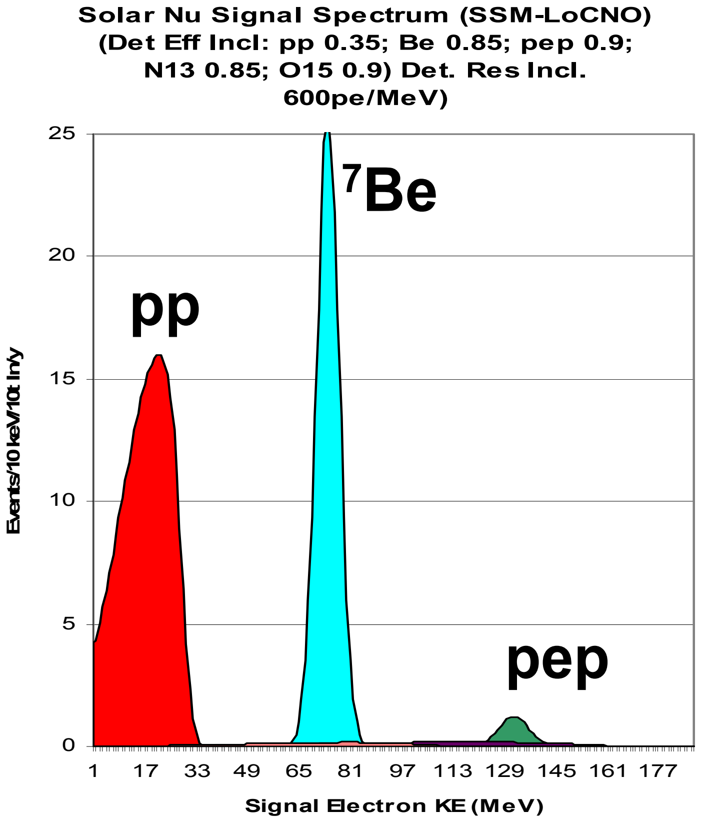


Figure 4: Solar neutrino spectrum observable in practice in LENS-Sol

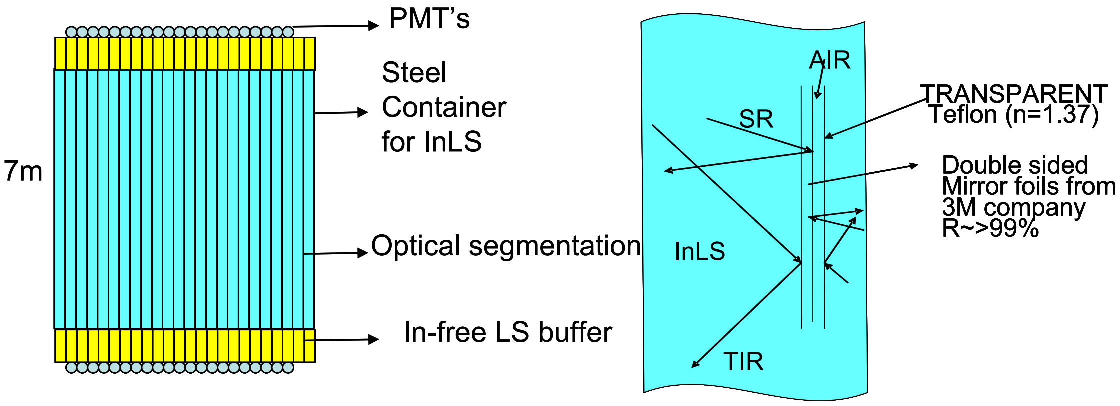


Figure 5: Conceptual design of LENS-Sol. The optical segmentation in the detector tank is achieved by a cage of light pipes that convey the signal light to the PMT's via TIR and specular reflection.

Hyper Scintillation Detector (HSD):
[Learned, Pakvasa (U Hawaii) Svoboda (LSU) Feilitzsch, Oberauer (Tech. U. Munich), Scholberg (Duke U), Vogelaar, Pitt, Takeuchi, Lay Nam Chang , Raghavan (VT)].

The objectives of the detector will cut across a wide swath of frontier questions in basic science that can be answered only by a detector of this type. The science portfolio of HSD includes topics in:

1. Geophysical structure and evolution of the Earth studied via global observation of anti-neutrinos from the earth's interior
2. Supernova astrophysics and cosmology (observation of live supernovae; detection of the supernova relic background)
3. Elementary particles: (deep search for the decay of the proton; long baseline experiments using high energy neutrinos from BNL or Fermilab.

The basic advantages of this multi-disciplinary scintillation approach are:
1) sensitivity to events of *both low and high energy,* ranging 4 orders of magnitude from ~100 keV to ~1 GeV;
2) high sensitivity to heavy particles that are invisible in Cerenkov detectors;
3) high sensitivity to antineutrinos that can be specifically tagged by capture on protons (of importance to all the above topics).

The concept of a very large detector of this kind can be best justified if it is shown to address a wide swath of frontier questions in several disciplines. The HSD satisfies this criterion exceedingly well. The science questions 1) and 2) can be addressed only in a scintillation type device sensitive to low energies (as opposed to Cerenkov or liquid argon technologies. In addition it brings comparable sensitivities to question 3) with a detector mass some x10 smaller than a Cerenkov detector.

Geophysical Neutrinos in HSD

The fundamental aim of this research is to determine the validity of present geophysical models via "whole earth" data. The key foundations of the present model are 1) the heat budget of the earth; and 2) the distribution of radioactive elements in the earth's interior; 3) the relative abundance of U, Th conforming to solar system abundances.
Geophysical antineutrino research is at the same stage as the beginning of solar neutrino research for understanding the solar interior with the advantage that powerful detection technology already developed in the context of the latter are now at hand. The above objectives are uniquely well served via a network of massive antineutrino detectors placed suitably at favorable locations The proposed HSD with 100 kT of LS will be the most massive detector. Current estimates show that in the main campus of the Kimballton-DUSEL at a depth of ~4000 to 4500 feet, it may be possible to reach an antineutrino flux sensitivity down to a few antineutrinos/cm^2/s even at ~5 MeV.

The earth is a rich source of antineutrinos of energy 0-10 MeV that are observable in HSD with high discrimination against background because of the availability of a secure delayed coincidence neutron that can tag the positron signal of the antineutrino capture reaction on protons in the scintillator.. The geophysical sources are listed in the Table below and illustrated in Fig. 6

Source of Antineutrinos	**Location**
Radioactivity of U and Th	Crust, Mantle
Fission Reactor?	Core
Commercial Power Reactors	Surface

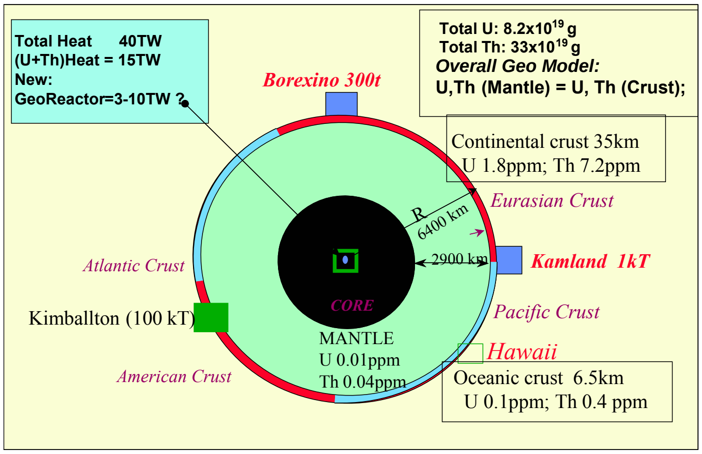


Fig. 6 Internal Energy Sources in the Earth and their Distribution

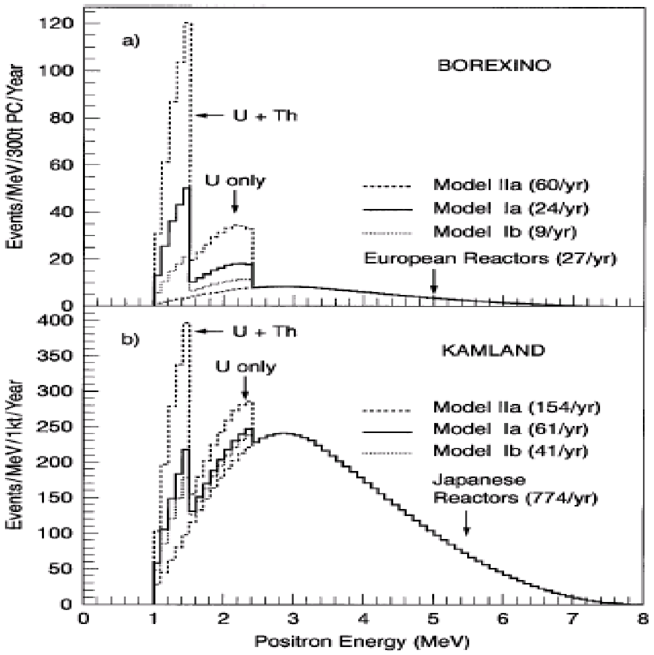


FIG. 2. $\bar{\nu}_e$ (positron) signal spectra from the Earth and from nuclear reactors at Borexino (a) and at Kamland (b). The signal rates point to several years of measurement for data of statistical significance to different aspects of geophysical interpretation.

Reactor bg/Kt/yr

Kamioka:	775
Homestake:	55
WIPP:	61
San Jacinto:	700
Kimballton:	~100

(RSR et al PRL 80 (635) 1998)

Fig. 7 Antineutrino spectra predicted for different geophysical models in BOREXINO and KamLAND.

Antineutrino spectra predicted by different models of the U, Th distribution in the earth are shown in Fig. 7. The spectra also depend on the location of the detector. The Kamioka location, while interesting because it is at the interface of continental and oceanic crusts, suffers from the close proximity of powerful surface nuclear reactors. The Borexino detector will have low reactor background, however it has too low a target mass to be sensitive to low fluxes in certain models. The background at Kimballon-DUSEL is expected to be low enough and the detector mass large enough to produce definitive results on the geophysical neutrino problem.

Supernova Astrophysics & Cosmology in HSD

a) Live Detection of Supernovae (SN): SN1987A showed the astrophysical importance of observing ν emission from exploding stars. The next observation needs to be much more detailed with spectroscopic inventories of the different types of neutrino species emitted in these events. The large mass of HSD makes an ideal SN ν detector with the following neutrino detection modes:

1) Antineutrino capture on protons can deliver the $\bar{\nu}_e$ component.
2) NC excitation to T=0 states in ^{12}C (15 MeV) in the LS facilitates the detection of neutrinos of all flavors.
3) ν-electron scattering (ES) provides a signal based on both NC and CC.

The SN burst is the overall tag for all these events. Individual tags available in the above reactions (except ES) help separate the flavor components of the neutrino emission. Thus a complete inventory of ν species can be made of a future SN event.

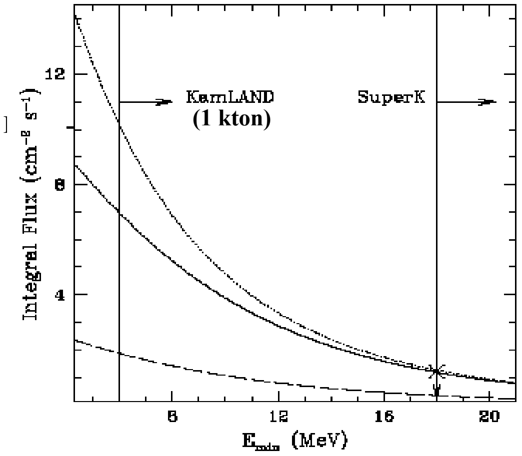


Fig. 8 Integral rates of supernova relic antineutrinos above a threshold E_{min} for different SRN models (L. E. Strigari et al, astro-ph/0312346). Relatively higher rates at low energies (inaccessible to SuperKamiokande) are observable in HSD (x100 larger detector mass compared to Kamland). It is the low energy rates that are sensitive high cosmological red shifts.

d) Supernova Relic Neutrinos (SRN):

The occurrence of SN that produces a ν flux detectable in earth devices is relatively rare. However, there should exist a diffuse, isotropic background flux of relic neutrinos from all *past* Type II SN (SNII) in the observable universe that could provide a new source of information on a) the basic picture of core collapse of SNII not only locally but also at high red shifts (z>1); b) the rate of occurrence of SN (proportional to star formation rate and the metal enrichment rate). The low SRN fluxes mandate detection of only the $\bar{\nu}_e$ component of the flux. Thus large detectors such as SK, KamLAND can be considered for the purpose, with the new possibilities available from HSD.

The spectrum of SRN, (see L. E. Strigari et al, astro-ph/0312346), is a typical Fermi-Dirac shape extending up to 30 MeV with integral fluxes >10 MeV typically in the range of 2/cm^{2}s. The interesting part of the spectrum is at low energies because of the sensitivity to red shifted $\bar{\nu}_e$ from far away SN and also because of the higher fluxes available in that window. However, the window contains also higher background. Thus, main advantages of HSD come into serious play in the problem. Fig. 8 shows the sharp increase in the integral SRN flux detectable in low threshold detectors such as KamLAND. It is estimated that KamLAND could make a 1σ detection of the SRN in 5ktY of data. The x10 target mass of HSD and its powerful $\bar{\nu}_e$ tag could reduce the time-to-discovery to <1yr of counting. HSD thus offers the greatest potential for the discovery and spectroscopy of SRN.

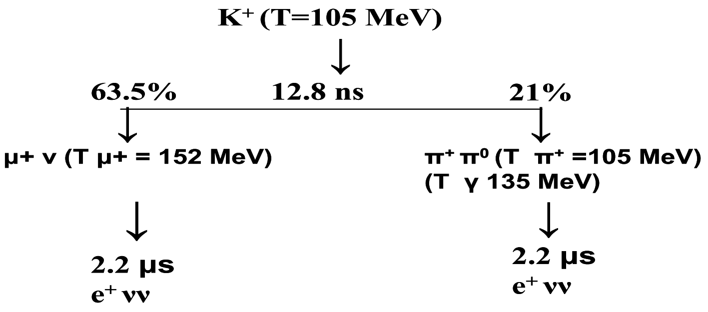
Proton Decay in HSD and other Large Detectors based on Cerenkov and Liquid Argon Technologies)

Large detectors (such as UNO and LANDDD) have been proposed for the rarest of events of interest to particle physics—viz. proton decay. Details of such proposals are accessible at: (UNO: http://ale.physics.sunysb.edu/uno/, LANDDD: http://puhep1.princeton.edu/~mcdonald/nufact/nrc_lanndd.pdf)

In this section we stress features particular to HSD. The main advantages in the scintillation approach to proton decay comes from:

1. The scintillation signal is x50 larger than the Cerenkov signal. Thus low energy spectroscopy of events down to 100 keV in energy becomes possible..
2. Heavy particles with energies below the Cerenkov threshold (see table below) can be observed with high sensitivity.
3. Low energy cascades correlated in time and space are particularly valuable for observing complex reactions cleanly and with low background.
4. Ultrapurity of organic LS solvents is technically much more feasible than water.
5. The technology of LS is established with >50years of experience and kton class detectors have been constructed and operated (comparable to Cerenkov and in contrast to LAr technology).

Triple Tag for p→$K^+ + \bar{\nu}$



Typical Cerenkov thresholds

- **Electron T=0.262 MeV**
- **Gamma E=0.421 MeV (Compton)**
- **Muon T=54 MeV**
- **Pion T=72 MeV**
- **Kaon T=253 MeV**
- **Proton T=481 MeV**
- **Neutron T~1 GeV (elastic scatter)**

The relevance of HSD to proton decay can be illustrated by its application to observing the prominent decay mode p→K v(bar) (see table above). Observation of this mode in the Cerenkov approach suffers from the fact that the initial K is below threshold and the only means is via the $\pi^+ \pi^o$ mode where the π^+ is just above threshold so that one depends heavily on the electromagnetic shower of the π^0 supplemented by the 6.3 MeV γ emitted when a proton hole state in ^{15}N. The efficiency then drops to ~8% so that one requires very large masses ~1 Megaton. The scintillation approach offers direct "gold-plated" events with a triple tag (see figure above) that allows all the members of the K and its decay cascade to be observed from proton (or neutron) decay. The efficiency is improved by ~x10 so that a 100 kT detector may be viable.

The additional low energy facility for proton decay arises uniquely in HSD from low energy sensitivity. A new approach to nucleon decay free of specific modes is to look at the highly excited residual nucleus (e.g. ^{11}C following neutron decay). The residual nuclei reach the low energy and ground states providing time-space correlated radiation that can tag the entire decay regardless of specific modes.

Long Baseline Neutrino Oscillations

The recent discovery of neutrino masses and mixings through solar, atmospheric, and reactor neutrino oscillation experiments has provided new clues to solving the mysteries of the Standard Model. Flavor mixing in the lepton-sector, together with the well-known mixing in the quark-sector, may lead to a new understanding of what `flavor' is, why there are three generations of fermions, and where their mass hierarchy comes from. CP violation in the neutrino-sector could potentially be large enough to account for the matter-antimatter asymmetry in the universe. A precise knowledge of the masses and mixing parameters will point to the higher energy theory that would explain, and replace, the Standard Model.

Assuming three-generation mixing, neutrino oscillations are sensitive to six parameters[1]: three mixing angles: θ_{12}, θ_{23} and θ_{13}; two mass-squared differences: $\delta m^2(21)$, $\delta m^2(23)$ and the CP-violating phase: δ(CP). Our current knowledge of these parameters is summarized as [2,3,4]: $\delta m^2(21),=(7.1^{+1.2}_{-0.6})\mathrm{x}10^{-5}$ eV^2; $\delta m^2(23) = (1.9\sim3.0)\mathrm{x}10^{-3}$eV^2; $\tan^2 \theta_{12} = 0.42\pm0.1$; $\sin^2 2\theta_{23} = 0.9$; $\sin^2 2\theta_{13} < 0.1$ with δ(CP) completely unknown. In order to measure these parameters with better accuracy and also to determine the yet unknown sign of $\delta m^2(23)$ and the value of the CP-violation phase δ(CP), several long-baseline (LBL) neutrino oscillation experiments are being planned which will observe the appearance of flavor converted species from ν_μ and $\nu_{\mu(\mathrm{bar})}$ beams created at accelerator facilites such as Fermilab, BNL, CERN, KEK, and JPARC.

Determining the sign of $\delta m^2(23)$ and the value of δ(CP) requires the detector to be placed at one of the appearance peaks which occur at

$$1.27[\delta m^2(23)(\mathrm{eV}^2)\mathrm{L}\ (\mathrm{km})]/E_\nu(\mathrm{GeV}) = \pi(n+1/2)$$

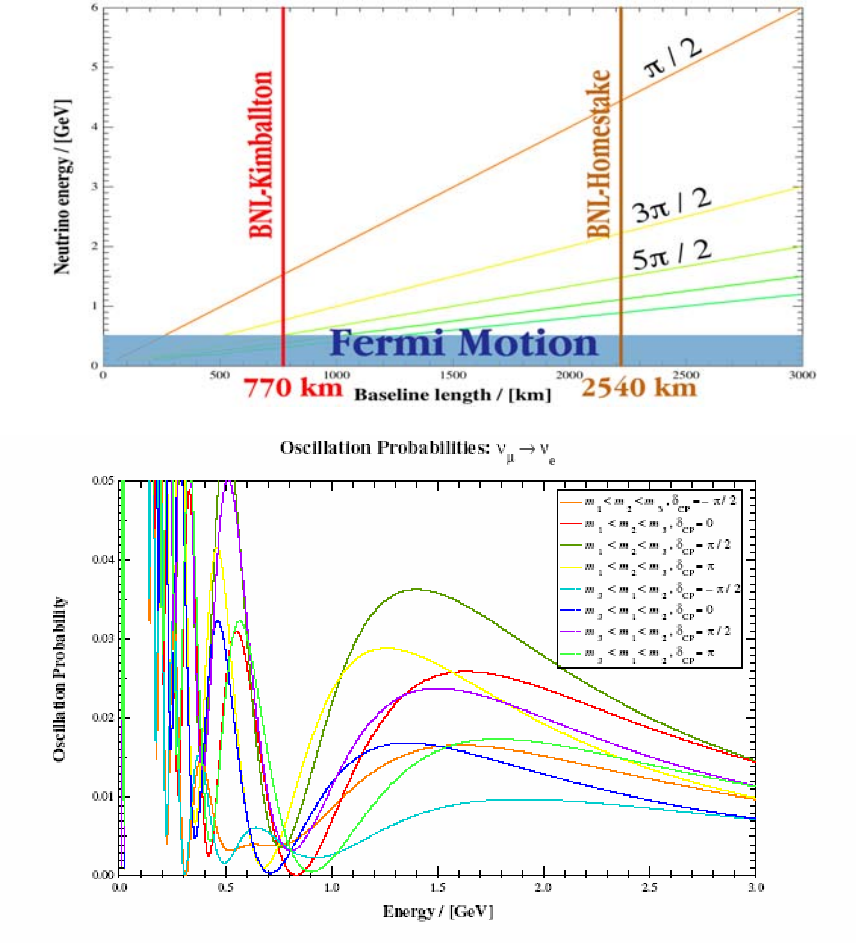


Fig. 9 (upper) Baseline length vs. neutrino energy relation. (Lower) $\nu_\mu \dashrightarrow \nu_e$ oscillation probability for a BNL-Kimballton experiment vs. neutrino energy

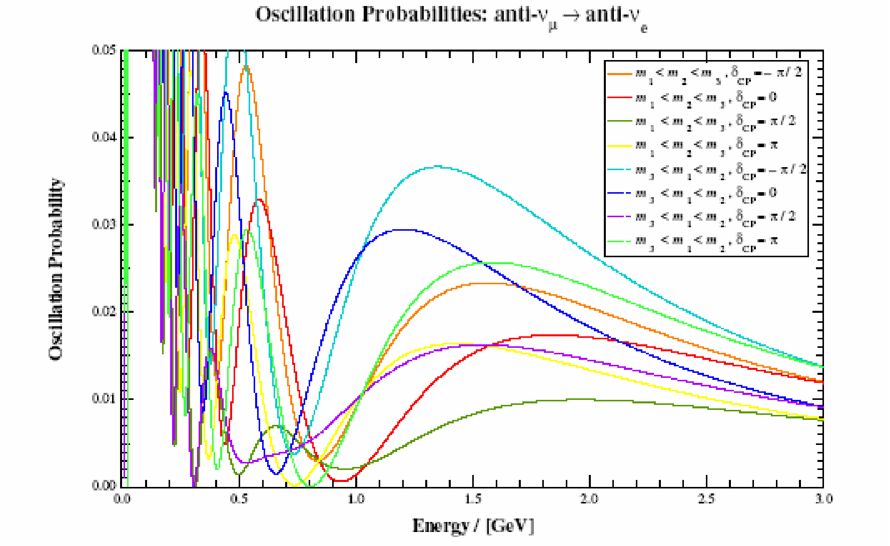


Fig.10 ν_μ(bar)→ ν_e(bar) oscillation probability for a BNL-Kimballton experiment

For $\delta m^2(23) = (1.9\sim3.0)\text{x}10^{-3}\text{eV}^2$ and L=770 km, the distance of Kimballton-BNL, the first appearance peak (n=0) occurs in the energy range E_ν = 1.9 GeV (see Fig. 6). This value is above the 0.5-1GeV bound below which detection is limited by the Fermi motion in nuclei and overlaps precisely with the planned wide band neutrino beam from the upgraded AGS accelerator [5]. This makes Kimballton the ideal location to place a detector that takes advantage of the BNL beam.

This is in stark contrast to the JPARC to Super-Kamiokande (T2K) experiment, for instance, which has a baseline of L = 295 km. In this case, the corresponding peak is expected in the energy range E_ν = 0.45-0.72 GeV, below the Fermi motion bound so that only the higher energy tail of the oscillation peak is available for analysis.

To obtain an idea of what type of signal can be seen at Kimballton, we present the expected $\nu_\mu \rightarrow \nu_e$ and ν_μ(bar)$\rightarrow$ ν_e (bar) oscillation probabilities in Fig. 9 and 10 for the parameter choice $\delta m^2(23) = 2.5\text{x}10^{-3}\text{eV}^2$ and $\sin^2 2\theta_{13} = 0.04$ with all other parameters set to their respective central values. The dependence of the probability profile on the sign of $\delta m^2(23)$ and the value of δ(CP) is shown. Due to matter effects, the probability for the normal (inverted) hierarchy is enhanced (suppressed) for neutrinos, and vice versa for anti-neutrinos. However, CP-violation effects obscure the separation, and there is degeneracy between the possibilities: $m_2<m_3$, δ(CP)<0 and $m_2>m_3$, δ(CP)>0. Lifting of these degeneracies can be accomplished through the careful measurement of the energy profile of the probabilities [6,7]**.** The Minakata-Nunokawa plot in Fig. 11 [6] also shows the energy- and δ(CP) dependence of the oscillation probabilities and illustrates how the degeneracy can be resolved through measurements at different energies.

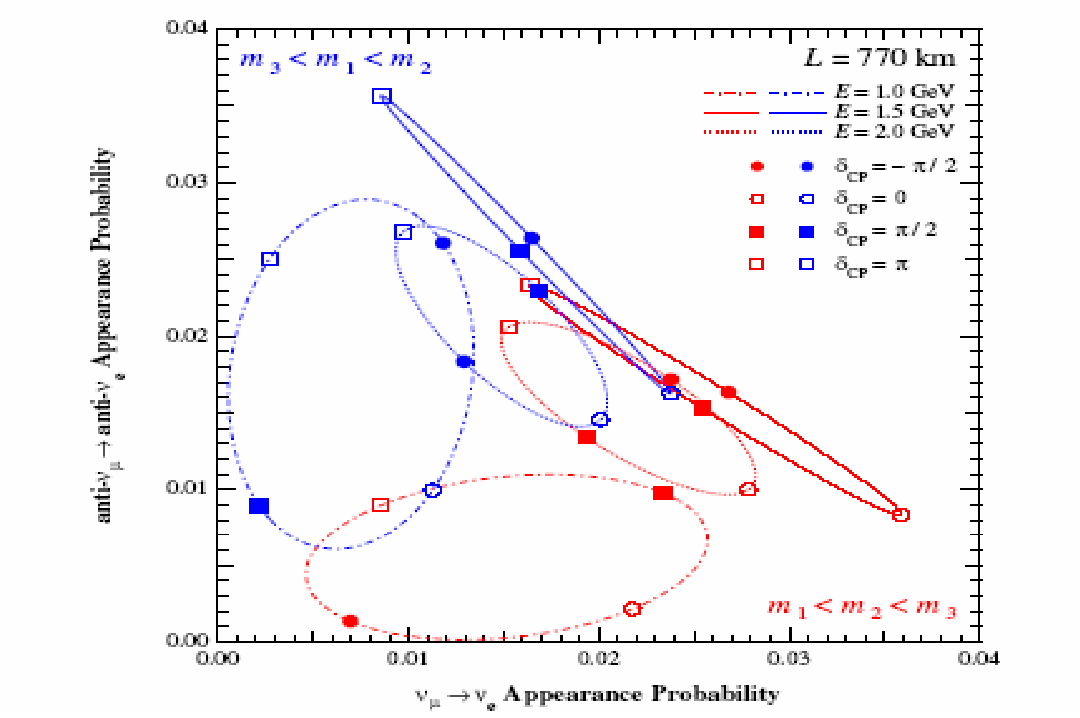


Fig. 11 Minakata-Nunakova plot for E = 1.0, 1.5 and 2 GeV

An estimate of the number of events for a BNL→Kimballton experiment is shown in Fig. 12 for a 500~kton water Cherenkov detector for 5 years of data taking. Given the proximity of Kimballton to BNL, the number of events is significantly higher than if the detector were placed elsewhere. The problem is whether this signal can be separated from the background, the most significant of which is the neutral current π^0 events which mimic electron appearance. However, this background is common to all Cerenkov detectors that work in this energy range (1-3 GeV), such as Super-Kamiokande and NOνA [8]. Preliminary studies for the UNO detector [9] conclude that this particular background can be controlled.

It is in this context that a liquid scintillation approach with HSD may be considered relevant. In this detector (100 kT), though the mass is lower, the background problems above can be bypassed especially in ν_μ(bar) → ν_e(bar) appearance experiments. The ν_e(bar) can be detected in HSD via delayed coincidence neutron tag and the energy resolution is superior to Cerenkov detection. The ν_μ(bar) flux at the accelerator is not significantly different at ~1GeV from that of ν_μ. (see Fig. 13 for expected rates at Kimballton HSD). Thus the baseline, the energy range and the almost background free detection of the ν_e(bar) signal makes a coherent experimental basis for a 100 kT HSD for LBL studies at Kimballton despite a lower signal rate because of the lower detector mass. The HSD is thus cost competitive to the proposed Cerenkov and Liquid Argon detector approaches with much higher masses up to 1 megaton, operating at very long baselines ~2500 km with much higher intensity neutrino beams.

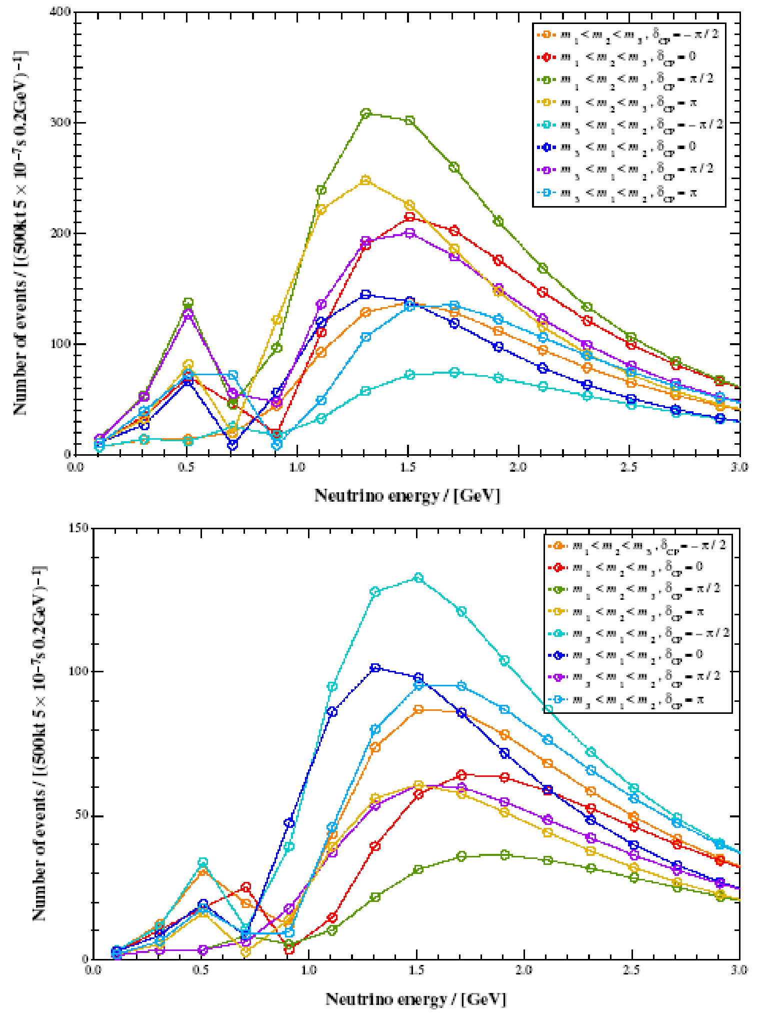


Fig. 12 Expected rates for a BNL-Kimballton experiment with 500 kton water Cerenkov detector. ν_μ -->ν_e (upper) and ν_μ(bar) -->ν_e(bar) (lower) figures.

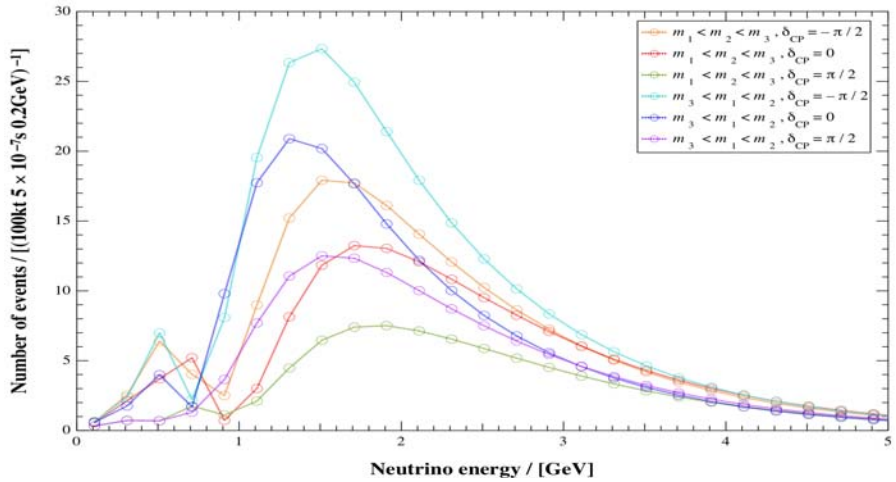


Fig 13 Expected ν_μ(bar)→ ν_e(bar) appearance signal for a BNL-Kimballton experiment with 100 kT scintillation approach (HSD

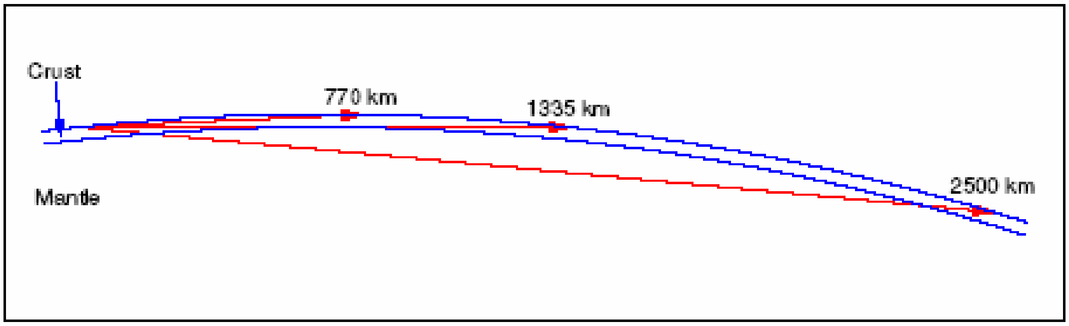


Fig. 14 The trajectory of the neutrino beam through the earth depending on the baseline length. The earth's crust is taken to be 35 km thick.

In the above discussion, the matter effect was assumed to be completely known. However, once the sign of $\delta m^2(23)$ is determined, a careful comparison of the $\nu_\mu \rightarrow \nu_e$ and ν_μ(bar)→ ν_e(bar) rates is necessary to determine δ(CP) to high accuracy. This also requires one to disentangle the genuine CP-violating effects from the fake CP-violating matter effects, which demands a good understanding of the density profile of the matter that the beams go through. This may become a problem once the baseline length exceeds ~1300 km since beyond that distance the beam will have to traverse the Earth's mantle to reach the detector [10] (see Fig. 14). Ref [11] has analyzed the potential impact the uncertainty on the matter effect will have on the extracted CP-violating phase, and they conclude that a meaningful separation between fake and genuine asymmetries will be difficult beyond ~1000 km.

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