Compact Neutrino Sources for π^+ Decay-at-Rest Experiments

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Physics opportunities for Decay-at-Rest (DAR) sources are highlighted in G. Karagiorgi's note in this session. Key is that the DAR spectrum is essentially devoid of $\bar{\nu}_e$, inasmuch as most all pi minus produced are absorbed before decaying. The spectrum is well suited for appearance of $\bar{\nu}_e$ employing inverse beta decay in detectors with free protons (water Cherenkov or liquid scintillator).

This note addresses the accelerator requirements and work to date towards developing the compact, cost-effective accelerator systems needed to address these opportunities, in particular using requirements for the DAEδALUS experiment deploying neutrino sources at 1, 8 and 20 km from the large LBNE detector at the Sanford Underground Research Facility (SURF) in South Dakota.

Proton beams of 800 MeV provide optimal production of π^+, maximizing the π^+ / π^- ratio. Matching the event rate anticipated for LBNE requires average beam powers of 1, 2 and 5 MW. For identification of events only one accelerator can be running at a time, (a 20% duty factor is assumed), ramping the instantaneous power up by a factor of 5.

We are working on a cyclotron concept (L. Calabretta et al, arXiv:1107.0652) accelerating H_2^+ ions which offers excellent prospects for meeting the ambitious requirements given above. Stripping extraction to protons overcomes the difficult turn-separation problem, and so avoids a primary concern for beam loss at high energies. The low charge-to-mass ratio (2 protons for every charge) helps overcome the space-charge problem encountered at low energies. We are working through the long list of questions regarding the concept, and are developing an R&D program to address the most critical. To date no show-stopper problems have emerged.

Ion sources producing protons can be tuned for H_2^+ with excellent intensity and beam quality. We are working with a cyclotron company to mount a test using an existing source to design the central region of the Injector Cyclotron, which will accelerate up to 3 mA of H_2^+ to 50 MeV/amu. Designs for this Cyclotron are well along. The main cyclotron is an 800 MeV/amu Superconducting Ring Cyclotron with 8 sector magnets and a maximum field of 6T. Beam dynamics are being studied at INFN-LNS (Catania) and PSI (Villigen), and engineering studies of the sector magnet will commence shortly. A workshop of cyclotron experts will convene in Erice (Sicily) in December 2011 to further the design efforts.

Our timetable calls for establishment of design and cost baselines within about a year, and we are developing a roadmap for building and testing of prototypes. We will shortly begin planning for construction of the first neutrino source.

In the interim, experiments using these sources should be refined to develop specific flux requirements and configurations.

I. THE INTERNATIONAL DESIGN STUDY FOR A NEUTRINO FACTORY, THE IDS-NF

The baseline NF in the IDS-NF Interim Design Report (IDR) [1] remains the high-energy (E_μ=25 GeV) two-baseline facility and remains the best facility to accurately measure the remaining parameters in the 3 ν mixing parameter space, if it turns out that the value of θ_{13} is actually 3σ below the central value of the latest global fit ($\sin^2\theta_{13} > 0.005$) [2]. In the IDS IDR, in the case of large θ_{13} ($\sin^2 2\theta_{13} > 0.01$), the document describes the performance of a single baseline (L = 2000 km), lower energy facility (E_μ=10 GeV), termed the LENF that uses a 100 kT magnetized iron detector (MIND) as the far detector. At the recent IDS-NF meeting, we developed a strategy (again in the context θ_{13} being large) for a phased or staged approach for the LENF - the low-luminosity-low-energy Neutrino Factory, L^3ENF. The main points of this strategy are:

1. The facility is upgradeable to the full luminosity of the LENF (10^{21} useful μ/yr.).
2. The facility does not require a proton driver to begin the physics program (assumes the Fermilab proton improvement plan).
3. The facility does not include muon ionization cooling.
4. The facility begins with 40kT of MIND.

A schematic of the L^3ENF is given in Fig. 1. Under these assumptions, the L^3ENF has a luminosity reduction factor of 25 (0.04 of the baseline) and, as seen in Fig. 2, has a performance that is as good as or better than LBNE. This approach lowers the facility cost, reduces technical risk and allows for an earlier start. The upgrade path is then straightforward: add cooling when the technology is mature, add power when Project X in online and increase the detector mass to 100kT as funds become available.

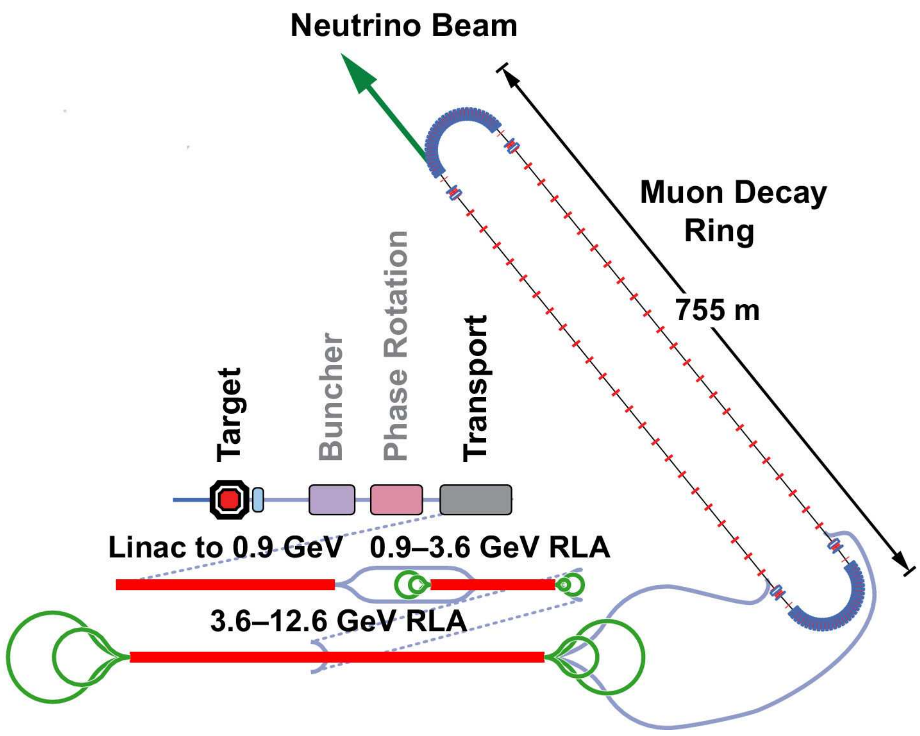

FIG. 1: Schematic of L^3ENF.

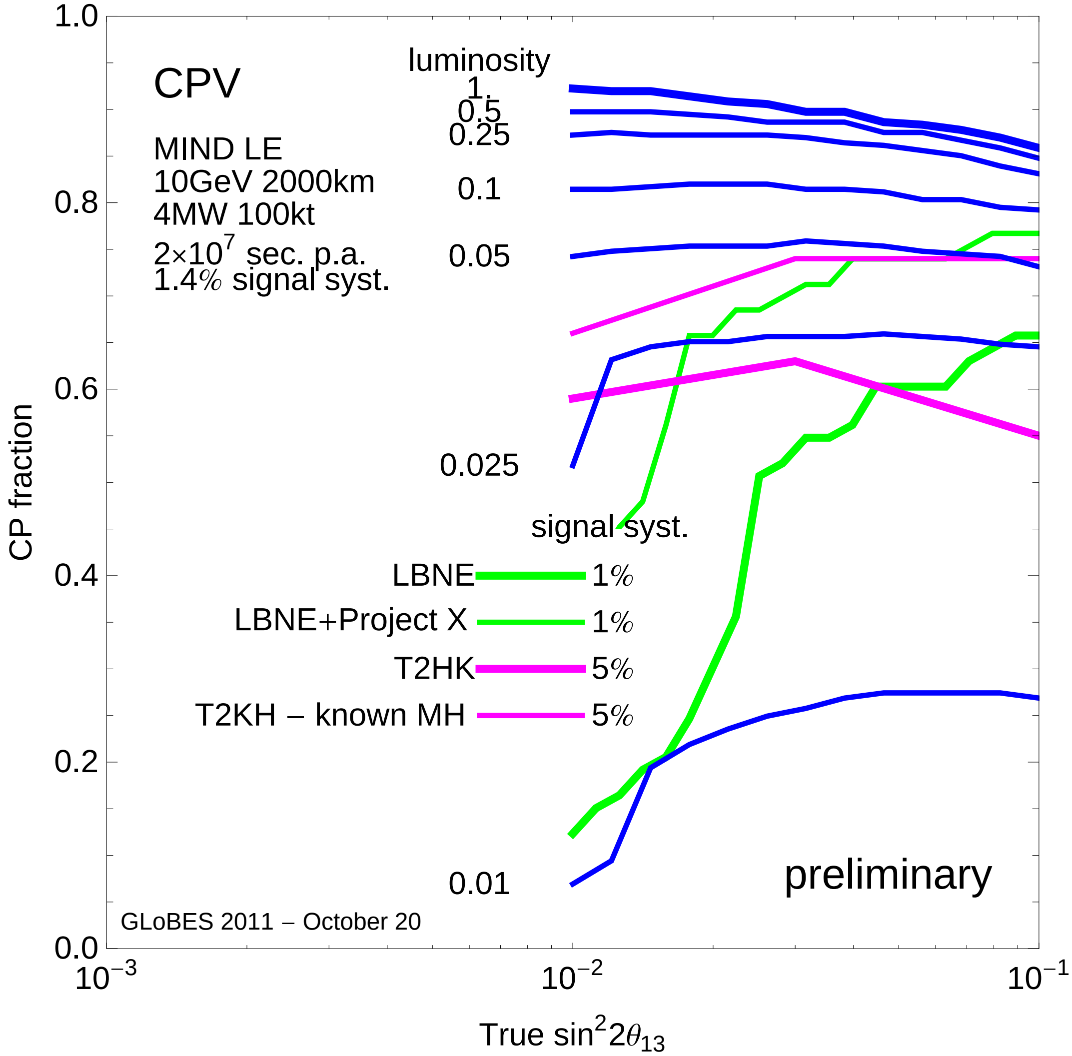

FIG. 2: CP fraction vs. true $\sin^2 2\theta_{13}$.

II. THE VERY-LOW-ENERGY NEUTRINO FACTORY (VLENF)

The Very-low-energy Neutrino Factory (VLENF) was also discussed at this meeting in the context of a near-term, relatively inexpensive facility that could:

1. Address the large δm^2 regime (LSND and MiniBooNE).
2. Make precision ν_e and $\bar{\nu}_e$ cross-section measurements.
3. Provide a technology test demonstration and μ decay ring instrumentation test bed.

The facility is very simple and consists of a conventional target station, a capture and transport section and injection into a race track ring with a straight length of between 50-75m, see Fig. 3 for a schematic of the facility. A number of decay ring designs have been studied, but a race-track FFAG with a center momentum of 2 GeV/c and a momentum acceptance of ± 20% looks very promising [3]. Fig. 4 shows the appearance sensitivity for this facility assuming 10^{21} protons on target, a 2 GeV/c center momentum FFAG race-track decay ring and an 800T

MIND-like detector at a baseline of 600m. At this point, the uncertainty on the backgrounds was assumed to be 20%. As can been see from Fig. ??, this facility has the potential to give unprecedented performance in the large δm^2 regime. In addition, the μ storage ring presents the only way to obtain large samples of ν_e events for cross-section measurements and presents the only experiment that can measure ν_e and ν_μ cross-sections in the same experiment. The next generation of long-baseline oscillation experiments will face a significant challenge in order to get systemtic errors to the 1% level. Gaining a better understanding of ν_e and $\bar{\nu_e}$ cross sections will be crucial to these future experiements. The energy range of interest is between 1 and 3 GeV and the VLENF is well suited to cover this range.

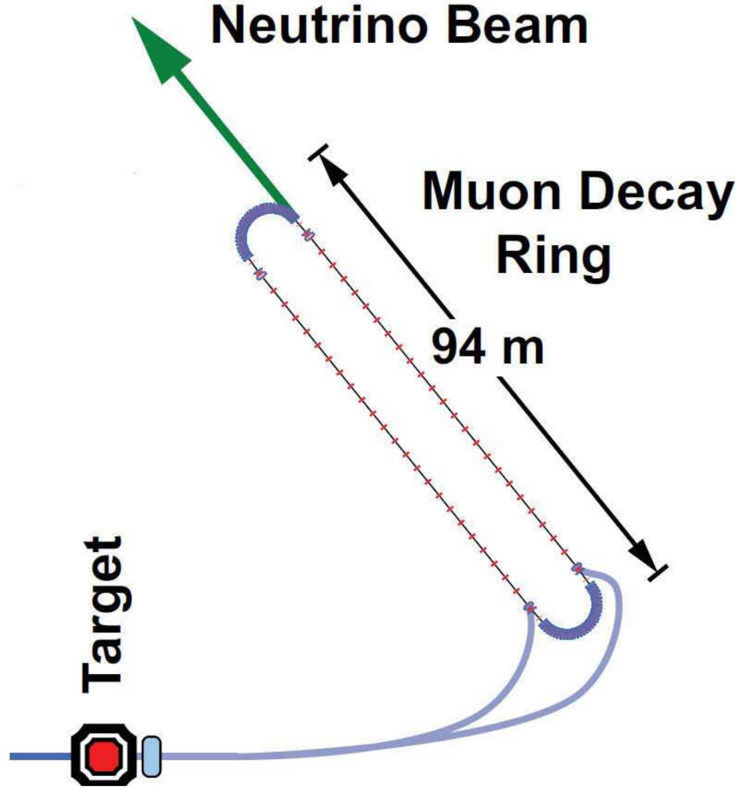

FIG. 3: Schematic of the VLENF.

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[3] Y. Mori, 7th IDS-NF Plenary Meeting, 17-19 October 2011, Virginia Tech Research Center in Arlington, VA. https://www.ids-nf.org/wiki/VTECH-2011-10-17/Agenda.

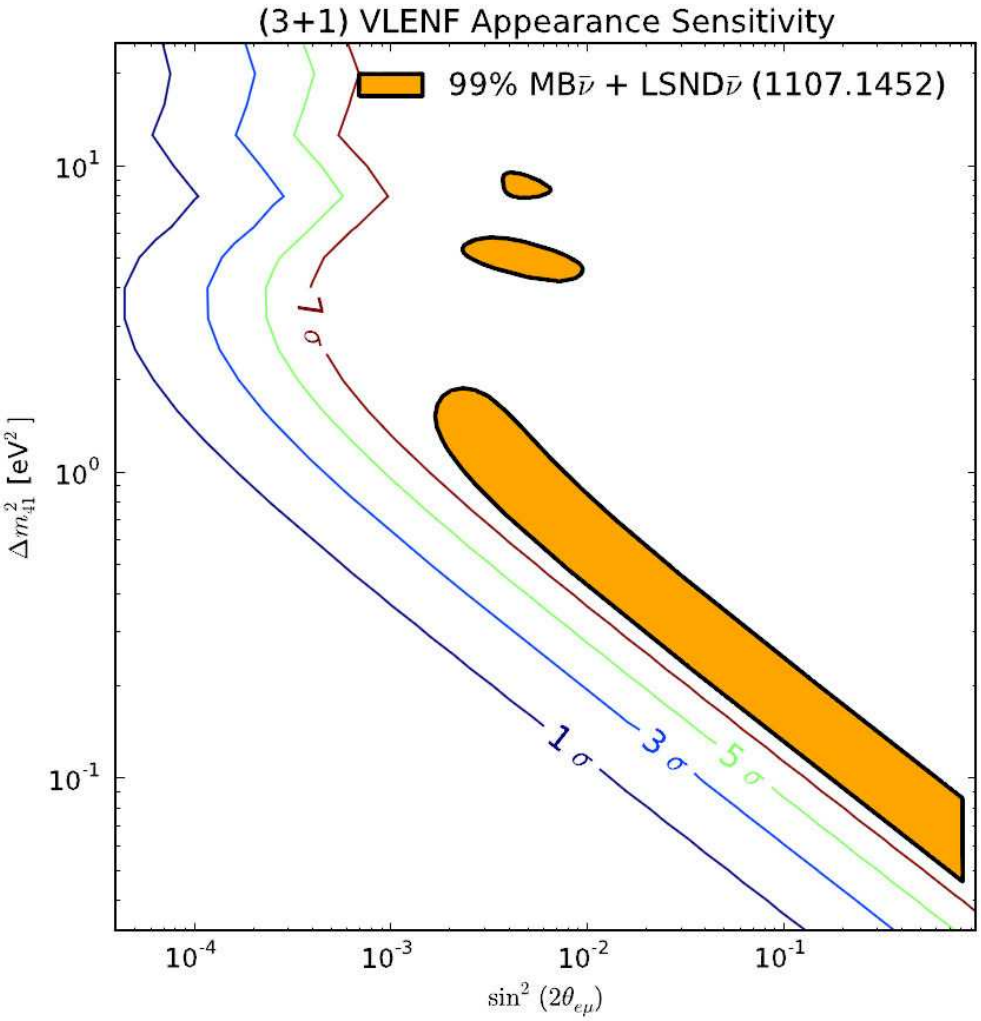

FIG. 4: 3+1 VLENF appearance sensitivity.

Neutrino scattering from Hydrogen and Deuterium: What can we still learn?

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1. Introduction

Neutrino scattering can give precise flavor and valence/sea separations of parton distributions, and by scattering off the simplest nuclei known, we can best understand the parton distributions in free nucleons. Those distributions not only provide powerful constraints for proton collider measurements, but then can be leveraged against measurements on more complicated nuclei to best understand the nuclear enviornment. This in turn means that we can separate out measurements of nuclear structure from measurements of nuclear effects.

By comparing neutrino and anti-neutrino scattering on deuterium, one can finally understand if there is charge symmetry violation in the nucleon, which is something that have been suggested as the source of the NuTeV anomaly [1]. Alternatively, one can simply try to measure the weak mixing angle using the Paschos-Wolfenstein relation on the simplest isoscalar target, Deuterium.

There have been no neutrino measurements on hydrogen or deuterium since the bubble chamber era when neutrino beams were orders of magnitude less intense than the neutrino beams available today. With the beams that would become available in the Projext X era, one could do measurements on for example a three hundred kilogram cryogenic target and still get hundreds of thousands of events in a year long run.

2. Experimental Considerations

Two important ingredients for this measurement are of course the neutrino beam and the volume of liquid hydrogen or deuterium that is available. Studies have been done to study the physics reach for those targets [2], assuming the 2200 litre cryogenic vessel that is current operating with He underground in the NuMI beamline in front of the MINERvA detector[3]. The vessel is mechanically and cryogenically equiped to operate with either hydrogen or deuterium H_2 or D_2. Because the cryogenic target is not instrumented, there is a loss in acceptance since final state particles must leave the vessel to be detected in MINERvA [2]. Nevertheless, with a 1 year each neutrino and antineutrino run in the NuMI high energy configuration, (peak neutrino energy at 14 GeV) assuming 6×10^{20} protons on target per year, the sensitivity to the d/u ratio is quite impressive, as shown in figure 1. In the Project X era, the protons on target per year is expected to be over a factor of three above this rate, so the figure below could be reached in even less time, allowing for other measurements with deuterium to be made. It should be noted that in order to reach this level of experimental precision the flux uncertainties associated with neutrino versus antineutrino running must be kept under control.

One important aspect that must be addressed for these measurements to take place is the feasibility of storing large quantities of liquefied flammable gas in a deep underground location. There are currently investigations of what would be required to allow a measurement like this to proceed in the NOνA era. If the risk is too large to operate such a target deep underground, then these measurements would need to be made with a neutrino beam that has at least onne detector hall that is at ground level.

Ultimately a bubble chamber followed by downstream tracking, calorimetry and a muon spectrometer would provide a higher acceptance for events on hydrogen and deuterium than the configuration described above, since the threshold for seeing a final state proton would be significantly lower. The slower time response of the bubble chamber technology would have to be an inupt to the neutrino beam design, however, since the bubble formation takes a few milliseconds and would then have to be read out in between each neutrino beam spill. But the physics reach of such a device would surpass even the reach shown in figure 1.

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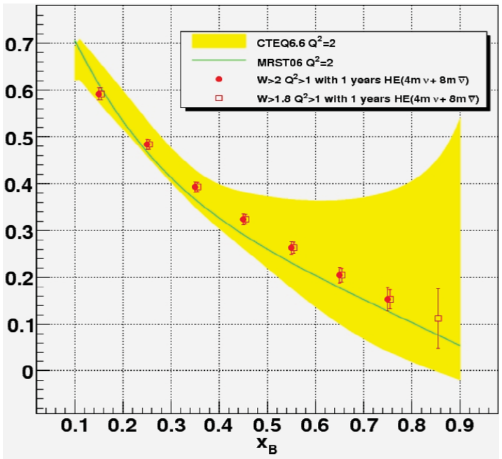

Figure 1: Statistical precision of a measurement of d over u quark distribution in hydrogen, for a 1 year run with neutrinos and antineutrinos with a high energy neutrino beam, as described in the text.

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Search for Sterile Neutrinos with a Radioactive Source at Daya Bay

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Data from a variety of short-baseline experiments as well as astrophysical observations and cosmology favor the existence of additional neutrino mass states beyond the 3 active species in the Standard Model. Most recently, a re-analysis of short-baseline reactor neutrino experiments found a 3% deficit between the predicted antineutrino flux and observations [1]. This has been interpreted as indication for the existence of at least one sterile neutrino. with a mass splitting of $\sim 1\text{eV}^2$ [2]. The possible implications of additional sterile neutrino states would be profound and change the paradigm of the Standard Model of Particle Physics. As a result, great interest has developed in testing the hypothesis of sterile neutrinos and providing a definitive resolution to the question if sterile neutrinos exist [3, 4].

We propose to use the far site detector complex of the Daya Bay reactor experiment together with a compact PBq $\overline{\nu}_e$ source as a location to search for sterile neutrinos with $\geq$ eV mass [5]. The Daya Bay reactor experiment is a next-generation reactor experiment under construction at the Daya Bay Nuclear Power Plant near Shenzhen, China and designed to make a high-precision measurement of the neutrino mixing angle θ_{13} using antineutrinos from the Day Bay reactor complex [6]. The experiment has three underground sites, two at short distances from the reactors ($\sim$300 m) with two $\overline{\nu}_e$ detectors each, and one at a further baseline ($\sim$1.8 km) with four $\overline{\nu}_e$ detectors. The far site detector complex of the Daya Bay reactor experiment houses four 20-ton antineutrino detectors with a separation of 6 m.

When combined with a compact radioactive $\overline{\nu}_e$ source the Daya Bay far detectors provide a unique setup for the study of neutrino oscillation with multiple detectors over baselines ranging from 1.5-8 m. The geometric arrangement of the four identical Daya Bay detectors and the flexibility to place the $\overline{\nu}_e$ source at multiple locations outside the antineutrino detectors and inside the water pool allows for additional control of experimental systematics. Daya Bay's unique feature of being able to use multiple detectors and multiple possible source positions will allow us to cross-check any results. In addition, the water pool surrounding the four far-site Daya Bay detectors provides natural shielding and source cooling minimizing technical complications resulting from a hot, radioactive source. As a source we propose to use a heavily shielded, 18.5 PBq ^{144}Ce source approximately 16 cm in diameter ($\Delta Q = 2.996$ MeV).

This experimental setup can probe sterile neutrino oscillations most powerfully by measuring spectral distortions of the energy and baseline spectrum. If the source's $\overline{\nu}_e$ rate normalization is well-measured, further information can be provided by measuring total rate deficits. The dominant background of this experiment, reactor $\overline{\nu}_e$, will be measured to less than 1% in rate and spectra by the near-site detectors. In addition, the detector systematics of all detectors will be well-understood after 3 years of dedicated θ_{13} running, minimizing expected detector-related systematics.

The proposed Daya Bay sterile neutrino experiment can probe the 0.3-10 eV^2 mass splitting range to a sensitivity of as low as $\sin^2 2\theta_{new} < 0.04$ at 95% CL. The experiment will be sensitive at 95% CL to most of the 95% CL allowed sterile neutrino parameter space suggested by the reactor neutrino anomaly, MiniBooNE, LSND, and the Gallium experiments. In one year, the 3+1 sterile neutrino hypothesis can be tested at essentially the full suggested range of the parameters Δm^2_{new} and $\sin^2 2\theta_{\text{new}}$ (90% C.L.).

In order to realize such an experiment, R&D towards the development of a PBq $\overline{\nu}_e$ source must be conducted. The process of selectively harvesting fission products from spent nuclear fuel has been developed in the nuclear reprocessing industry, and will need to be tailored to remove ^{144}Ce with high efficiency and purity from a small number of spent fuel assemblies. The necessary R&D and development work can be conducted in the years ahead during the θ_{13} measurement at Daya Bay.

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International Context

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Given the significant investment future neutrino oscillation experiments represent, international coordination seems to be at least prudent if not mandatory. In this short note, which is derived from a presentation given on October 24$^{\text{th}}$, 2011 at the pre-meeting of the neutrino working group of the Intensity Frontier workshop, we try to summarize the international context in which LBNE and Project X are likely to find themselves.

With the discovery of neutrino oscillation starting in the late 1990s precision studies of neutrino mixing have moved to the forefront of experimental high energy physics and numerous proposals, comparative studies *etc.* have been published to explore the possibilities for an experimental program to pursue this science, see *e.g.* [1]. Neutrino physics is, at this moment, at a transition from discovery to precision science and while some may find that this makes the field less exiting and vibrant, it should not be forgotten, that neutrino oscillation is the first sign of physics beyond the Standard Model whose discovery is not entirely due to astrophysics and cosmology. Therefore, precision studies of neutrino oscillation are the equivalent of precision studies of *e.g.* supersymmetric particles, if they should happen to be discovered at the LHC. In this sense neutrino physics is ahead of the program at the High Energy Frontier – the initial discovery of new physics has been made and now we need to follow up and understand what it is, we have discovered.

The initial discoveries in neutrino physics have largely been made using neutrino sources which already were available, either natural ones like the atmosphere or artificial ones like nuclear power reactors. The obvious advantage of these sources is their easy availability and the associated low cost. The drawback is, that the experimenter has no control over these sources and systematic uncertainties can be substantial. To make further progress, purpose-made neutrino sources will be necessary and this implies a transition to intense accelerator-driven systems with a concomitant increase in complexity and cost, while at the same time very large detectors are still needed to obtain sufficient statistics. These large detectors, if located deep underground, are also ideal tools to study low energy phenomena like supernova neutrinos, proton decay *asf.*. While this presents a true synergy, one cannot fail to notice that none of these non beam-related physics topics would warrant an investment at the required level and it is the beam-related precision oscillation physics which is the physics driver for this program.

In this note, we will limit ourselves to the description of the various alternatives to LBNE and Project X and their ability to study oscillations amongst three active flavors. This limitation is not inherent in the facilities, they all have significant capabilities towards new physics searches, but is due to the fact that this aspect has been studied most, especially in terms of a comparison of facilities. The overarching goal of studying three flavor oscillation with precision it to find out whether in neutrinos, like in the quark sector, all flavor transitions are described by a unitary 3×3 matrix or if there are contributions from new physics. The ultimate hope, the holy grail, is, of course, to solve the flavor puzzle. The precision study of neutrino oscillation can be broken down into the following questions: What is the size of $\sin^2 2\theta_{13}$? Is there leptonic CP violation? What is the ordering of the three mass eigenstates, or the mas hierarchy? Is the atmospheric mixing, as parametrized by θ_{23}, maximal? There is no particularly compelling way to rank these questions by their importance and depending on ones theoretical prejudices many different rankings seem to be equally valid. The magnitude of $\sin^2 2\theta_{13}$ has practical implications because it greatly impacts on the choice of an appropriate technology to pursue the other questions.

The past year has seen quite some excitement with indications that $\sin^2 2\theta_{13}$ maybe finite. Both, T2K [2] and MINOS [3] report signals which point in this direction and while each of these indications is below $3\,\sigma$ significance, global fits seem to already exclude $\sin^2 2\theta_{13} = 0$ at more than $3\,\sigma$ [4]; taken at face value the global fit implies that $\sin^2 2\theta_{13} > 0.02$ at the $3\,\sigma$ level. Fortunately, reactor neutrino experiments [5–7] will soon provide first results and also T2K will resume data taking, therefore we can expect a definitive answer to whether the current indications are correct or not sometime 2012. Since the answer to this question has profound implications for any future long baseline neutrino experiment, as we will demonstrate in the following, no major decision should be taken until the question of whether $\sin^2 2\theta_{13} > 0.02$ or not has been resolved.

In figure 1 we compare the physics sensitivities for the discovery of the mass hierarchy (left hand panel) and for the discovery reach for CP violation (right hand panel). Both panels show the fraction of true δ_{CP} for which the measurement can be performed at the $3\,\sigma$ confidence level as a function of the true value of $\sin^2 2\theta_{13}$. The various lines are for different experimental setups as indicated by the legend and the details of the experiments are given in the caption. The selection of possible experiments has been guided by whether there is a serious effort towards

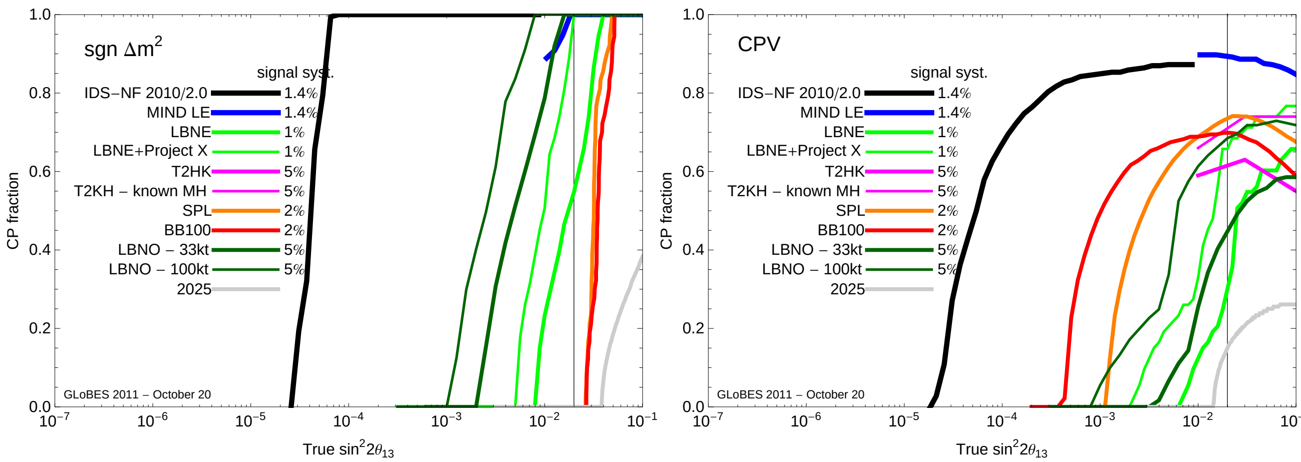

FIG. 1. The three flavor oscillation discovery reaches quantified by the fraction of true $\delta_{\rm CP}$ versus the true value of $\sin^2 2\theta_{13}$ at $3\,\sigma$ confidence level (1 dof) for the mass hierarchy (left hand panel) and for CP violation (right hand panel). The various lines are for different experimental setups as labeled in the legend, where also the systematic uncertainty on the signal normalization is given. IDS-NF 2010/2.0 is a two baseline neutrino factory setup with magnetized iron detectors of 100 kt at a baseline of 4 000 km and 50 kt at a baseline of 7 500 km using 10^{21} 25 GeV muons per year (10^7 s) for 10 years. MIND LE is a single baseline neutrino factory with one magnetized iron detector of 100 kt at a baseline of 2 000 km using 10^{21} 10 GeV muons per year (10^7 s) for 10 years; both neutrino factory setups are taken from [8]. LBNE is a 700 kW beam of 120 GeV protons running for 10 years (2×10^7 s, each) directed towards a 200 kt water Cerenkov detector (or a 6 times smaller liquid argon detector) with a baseline of 1 300 km. LBNE + Project X assumes the same setup, however with 2.3 MW beam power; the sensitivity for both setups is taken from [9]. T2HK assumes a 560 kt water Cerenkov detector and 1.66 MW 50 GeV proton beam for 5 years (10^7 s, each) with a baseline of 295 km and the sensitivities are taken from [10], where the curve labeled T2HK – know mass hierarchy, assumes the mass hierarchy to be known. The SPL setups assumes a 8 GeV 4 MW proton beam for 10 years (each 10^7 s) towards a 440 kt water Cerenkov detector over a baseline of 130 km, the sensitivities are taken from [11]. Note, that a re-optimized beam for the SPL has been shown to enhance sensitivities somewhat [12]. The BB100 setup is a $\gamma = 100$ beta beam towards a 440 kt water Cerenkov detector over a baseline of 130 km using 5.8×10^{18} ^{6}He per year (10^7 s) for 5 years and 2.2×10^{18} ^{18}Ne decays per year for 5 years [11]. Note, that within the EURISOL design study it was found that these ion intensities may be very difficult to reach [13]. Both setups BB100 and SPL include the atmospheric neutrino data sample which gives rise to some sensitivity towards the mass hierarchy. LBNO is a liquid argon detector of 33 kt or 100 kt (see legend) using a 1.7 MW 50 GeV proton beam for 10 years (1.7×10^7 s each) over a baseline of 2 300 km and the sensitivities are from [14]. Finally, the curve labeled 2025 summarizes our knowledge in the year 2025 if no facilities are built, but all beams, i.e. NuMI and the T2K beam are upgraded to 2.3 MW and 1.66 MW, respectively and is taken from [15]. All sensitivities, except the T2HK curves, have been computed using GLoBES [16, 17].

a machine and detector design. The two neutrino factory options are taken from the Interim Design report [8] of the International Design Study for the Neutrino Factory (IDS-NF). LBNE and LBNE + Project X are described in detail in the Physics Working Group report of LBNE [18]. The SPL setup is based on a possible low energy superconducting linac which used to be part of CERN's plan to upgrade its proton infrastructure for high luminosity LHC running. The BB100 setups represent a beta beam which could be realized with the existing PS at CERN and therefore, in principle, could be run concurrently with SPL. The machine options for both setups have been studied in the context of the Euro-ν [19] and EURISOL [13] programs. LBNO is developed in the context of the LAGUNA-LBNO study [20, 21], which currently includes three possible detector technologies, water, liquid argon and liquid scintillator and seven potential sites. The accelerator would be based on a possible upgrade/replacement of the PS at CERN. The results presented in figure 1 are valid for all values of $\sin^2 2\theta_{13}$ and for all values and both measurement the two baseline neutrino factory, IDS-NF 2010/2.0, performs best. It is worthwhile to point out that mass hierarchy sensitivities for BB100 and SPL, given their very short baseline of 135 km, is entirely due to the atmospheric neutrino sample collected in the 440 kt water Cerenkov detector. Therefore, it can be expected that T2HK would have a least the same sensitivity to the mass hierarchy for a similar exposure to atmospheric neutrinos. In absence of any knowledge of the true value of $\sin^2 2\theta_{13}$ it seems one would prefer a neutrino factory since it has the deepest reach in the $\sin^2 2\theta_{13}$ direction.

However, as mentioned previously, we have strong hints that $\sin^2 2\theta_{13} > 0.02$. In this case, it has been demonstrated [15] that existing experiments, *i.e.* Double Chooz, Reno, Daya Bay, T2K and NOνA, will not be enough to determine the mass hierarchy or discover CP violation at $3\,\sigma$ in a significant fraction of the parameter

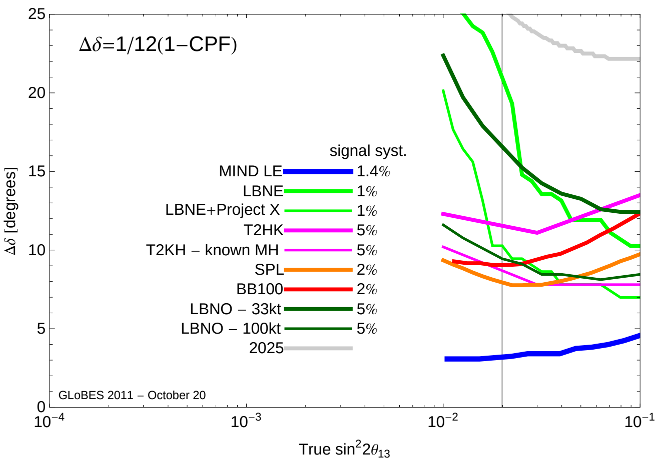

FIG. 2. The experimental setups are the same as defined in the caption of figure 1. Shown is the $1\,\sigma$ error on the CP phase, as defined in the text, as function of the true value of $\sin^2 2\theta_{13}$.

space even if $\sin^2 2\theta_{13} = 0.1$; only if the beams are considerably upgraded some sensitivity results as shown by the curve labeled 2025. In the large θ_{13} case the problem needs to be rephrased since the precise value of θ_{13} will be known in this case. As a result, the mass hierarchy measurement now should be accomplished by any, judiciously chosen, experiment. Thus, only CP violation remains as a distinguishing feature and the focus shifts from discovery to precision measurements. The effect this has on the perception of the relative merit of the various setups is illustrated in figure 2. This figure is obtained from figure 1 by taken the value of CP fraction, CPF and apply $1/12(1-CPF)$, which yields the average $1\,\sigma$ error on the CP phase where the average is taken between the true values for the phase of 0 and π. Obviously, in this representation the advantage offered by a neutrino factory, in this case the one baseline 10 GeV MIND LE setup, is significant as it improves the accuracy with respect to any other setup by a factor of two.

The real issue with a comparison of precision like the one in figure 2 is of course, that the results depends very strongly on the assumed value for systematics error. In this figure we chose to provide the systematic error on the appearance signal, as it has been shown to be the leading contribution to the overall systematic error budget [22]. At large θ_{13} the appearance signal can be sizable and thus statistical errors may well go down into the per cent range and per cent level systematics is no longer negligible. The values currently used are assumptions which in none of the cases has been substantiated by simulation. Past experience with pion-decay based neutrino beams shows that even reaching a systematic error of 5% can be challenging. This will be even more true for appearance experiments where both neutrino and antineutrino signals have to be compared with per cent level accuracy. Nuclear effects in neutrino interactions are currently not well known and therefore available event generators can not be considered reliable. Thus, the question arises whether these event generators can be used to predict the level of systematical errors in these experiments. To illustrate the problem: an experiment with 400 events and 1% systematics will have the same total error as an experiment with 10 000 events and 5% systematic error, thus even a moderate change in the systematics level can have a profound impact on the overall peformance in terms of precision. With respect to systematics, beams with *a priori* knowledge of the flavor composition and neutrino spectrum, like for instance beams from muon decay, offer enormous advantages. Thus, whatever the correct answer to the systematics question is, it seems fair to assume that neutrino factories will have smaller systematical errors than any of the other facilities. Systematical errors will control the precision of Standard Model parameter determinations and thus, also determine the level to which new physics can be found on top of the large Standard Model background, which is due to the leading $\sin^2 2\theta_{13}$ oscillation.

To summarize, all of the facilities discussed in this note are at relatively early planing stages, where LBNE is probably the most mature project. Most of the superbeam based approaches involve some sort of staging in either beam power or detector size. In this context it should be noted, that also a neutrino factory can be staged in luminosity and in its initial stage can avoid muon cooling and a dedicated proton driver. The time scale of all superbeam setups seems to be comparable, at least assuming a similar funding profile, which in practice may not be the case. Thus competition between superbeams seems likely and strategies to deal with schedule risks in this context should be developed, *e.g.* time lines of T2HK in comparison to Project X. This is even more true for large $\sin^2 2\theta_{13}$, where new results in 2012 could significantly affect the decision processes in all regions. As a result the perception of the US program being ahead may have to be revised. It also should be noted, that an aggressive program to control systematic errors will be required to optimally exploit the large θ_{13} case.

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Physics Opportunities with DAEδALUS

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DAEδALUS combines multiple $\pi^+ \rightarrow \mu^+$ decay-at-rest $\bar{\nu}_\mu$ sources with the 300 kton water Cherenkov detector being considered for LBNE (4850 ft level), doped with gadolinium. This experimental setup allows for a powerful search for CP violation in three-neutrino mixing.

The experimental configuration assumes three cyclotron accelerator complexes [1], at 1.5 km, 8 km, and 20 km each from the presently proposed detector location at DUSEL. Each complex produces an isotropic, high-flux ($4 \times 10^{22} \nu$/flavor/yr) $\bar{\nu}_\mu$ beam. The carefully chosen baselines allow sensitivity to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at the atmospheric Δm^2, which are dependent on θ_{13} and δ_{CP}. Rather than following the conventional approach of comparing oscillation probabilities for neutrinos versus antineutrinos ($\delta_{CP} \rightarrow -\delta_{CP}$) at the same L/E, the DAEδALUS search uses only antineutrinos, but compares oscillation probabilities at different L/E, exploiting the L-dependence of the CP-violating interference terms in the three-neutrino oscillation probability.

The signal $\bar{\nu}_e$ events are identified by the double-coincidence signature of Cherenkov light from the e^+ produced in inverse beta decays ($\bar{\nu}_e p \rightarrow e^+ n$) followed by light emitted in neutron capture on gadolinium. The beams are staggered, allowing the baseline for each event to be determined by timing. Assuming a 67% neutron capture efficiency, one expects on the order of a few hundred or more signal events for each baseline during a five year run, regardless of δ_{CP} and mass hierarchy, assuming $\sin^2 2\theta_{13} = 0.05$. Predicted backgrounds, including intrinsic beam $\bar{\nu}_e$ and non-beam backgrounds, correspond to roughly 950, 400, and 350 events for each baseline.

Assuming a ten year run, DAEδALUS' sensitivity reach for δ_{CP} and θ_{13} is found comparable to that of LBNE [2]. However, combining DAEδALUS and LBNE searches proves significantly advantageous, resulting in a factor of five improvement over either search (LBNE or DAEδALUS). The large increase in phase space coverage comes from the level of complementarity that LBNE and DAEδALUS share, one offering a high-statistics neutrino sample of higher energy, the other being a lower-energy high-statistics antineutrino search, which is also insensitive to matter effect induced degeneracies. With an additional ten year of simultaneous running with Project-X, the combination of the two searches gains an additional factor of three over either single search, giving 3σ sensitivity to values of $\sin^2 2\theta_{13} < 0.001$, and a 50% chance for δ_{CP} discovery (3σ) potential for $\sin^2 2\theta_{13} \sim 0.001$.

Aside from a potential independent confirmation of a θ_{13} and δ_{CP} measurement, or the increased sensitivity to θ_{13} and δ_{CP} that DAEδALUS offers, the DAEδALUS proposal also fits nicely within a wider physics program at DUSEL. By construction, the detector requirements for DAEδALUS overlap with the <100 MeV physics searches for supernova, relic neutrinos, and proton decay. In addition, the new accelerator facility (near) and neutrino (multi-)source at DUSEL provides opportunity for new experiments and enhancement of the DUSEL neutrino program. To date, the consideration of such source has prompted proposals for several searches for new physics. Those include searches for coherent neutrino scattering, non-standard neutrino interactions, sterile neutrino oscillations, axion searches, and low-Q^2 measurements of $\sin^2\theta_W$.

The combination of LBNE with a large water Cherenkov detector at DUSEL and DAEδALUS is worth being further explored, as it allows for a stronger and more well-rounded physics program for the intensity frontier, covering high energy neutrino physics and decay-at-rest source antineutrino physics, but also lending itself to and strengthening other fields such as particle astrophysics.

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Model-Independent Neutrino Oscillation Diagram

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L-E diagram

Although the Neutrino Standard Model (νSM), three massive neutrino oscillations with the Standard Model, successfully describes most of the current oscillation data, the question remains about short-baseline anomalies, including LSND signal, MiniBooNE excesses, and reactor anomaly [1]. If these signals are hints of new physics, there is a chance that they will not exhibit the standard L/E oscillatory dependence. The world neutrino oscillation data are usually mapped on the $\Delta m^2 - \sin^2 2\theta$ space (so called "MS-diagram"). However, this model-dependent diagram might mislead if neutrino oscillation signals are not based on neutrino masses.

The L-E diagram is a model-independent plot to map oscillation signals from different experiments. Here, massive neutrino oscillation solutions (=L/E oscillatory dependence) are represented by the line $L \propto E$. Data are consistent with two L/E neutrino oscillations, $\bar{\nu}_e$ disappearance measurement at the KamLAND experiment (2 to 8 MeV), and ν_μ and $\bar{\nu}_\mu$ disappearance measurements at the long-baseline and atmospheric neutrino experiments (300 to 2,000 MeV). Therefore, we know **there are at least two segments with $\mathbf{L \propto E}$ on the L-E diagram**. Nevertheless, our knowledge outside of these segments is limited. There are proposed models [2] which have L/E oscillatory dependences in these energy ranges so that models are consistent with current data, but have completely different dependences at the outside of them. These alternative models are interesting because they have a chance to reproduce short-baseline anomalies.

In conclusion, new experiments mapped on L-E diagram not previously explored are generally interesting.

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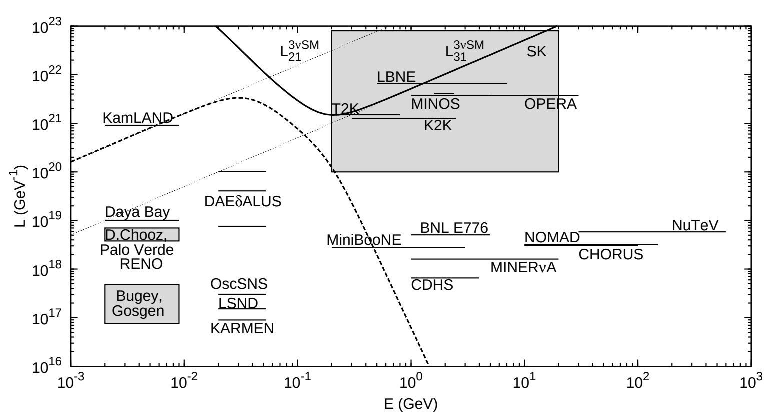

Figure 1: L-E diagram with νSM (two straight lines) and Puma model [1] (two curves).

The Connection Between Neutrino CP Violation and Leptogenesis

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A major motivation to look for CP violation in neutrino oscillation is that its observation would make it more plausible that the baryon-antibaryon asymmetry of the universe arose, at least in part, through leptogenesis. Leptogenesis, a natural outgrowth of the see-saw theory of why the observed neutrinos are so light, depends on the early-universe decays of very heavy neutrinos. In straightforward versions of leptogenesis, these heavy neutrinos must have masses of 10^9 GeV or more, so that, at least for a long time to come, we will not be able to confirm their existence directly by producing them at an energy-frontier collider. Instead, the hypothesis of leptogenesis must be explored indirectly through intensity-frontier experiments with the light neutrinos ν to which the heavy ones N are related by the see-saw.

The straightforward (type-I) see-saw model adds to the Standard Model (SM) particles only the heavy neutrinos N_i, which are taken to be right-handed electroweak singlets. The N_i are given very large Majorana masses, and Yukawa couplings $\mathcal{L} = y_{\alpha i}\bar{L}_\alpha \bar{H} N_i$ to the SM lepton doublets L_α, with $\alpha = e,\ \mu,\ \tau$, and the SM Higgs doublet H. These Yukawa couplings are responsible for the decays of the N_i. Assuming there are three N_i, to match the number of SM families, there are 9 Yukawa coupling constants $y_{\alpha i}$. If there are CP-violating phases in these Yukawa coupling constants, the decays $N_i \to L_\alpha + H$ and $N_i \to \bar{L}_\alpha + \bar{H}$ have different rates. Thus, in the early universe, these decays would have produced a world with unequal numbers of SM leptons and antileptons. SM processes would then have converted this world into one with unequal numbers of SM baryons and antibaryons, which is what we see today.

The see-saw picture contains 21 leptonic parameters. Of these, only 12 can be measured experimentally without producing the heavy neutrinos N. Since $21 > 12$, current laboratory measurements obviously cannot pin down what happened in the early universe. Oscillation of the light neutrinos ν can violate CP even if there was no leptogenesis. And leptogenesis may have occurred even if light-neutrino oscillation does not violate CP. However, neither of these possibilities is likely [1]. To see why, consider the see-saw relation that follows from the see-saw picture, namely

$$U M_\nu U^T = -\nu^2 (y\, M_N^{-1} y^T) \tag{1}$$

In this relation, $\nu = 174$ GeV is the vacuum expectation value of the Higgs field. All the other quantities are 3×3 matrices. The matrix U is the leptonic mixing matrix, M_ν is a diagonal matrix whose diagonal elements are the masses of the light neutrinos, y is the matrix of Yukawa coupling constants $y_{\alpha i}$, and M_N is a diagonal matrix whose diagonal elements are the masses of the heavy neutrinos. The quantities on the right-hand side of Eq. (1) are inputs to the see-saw model, while those on the left-hand side are consequences of the model. The quantities ν, M_ν, and M_N are all real.

Suppose leptogenesis occurred. Then y, whose CP-violating phases drive leptogenesis, cannot be real. Thus, barring a conspiracy between M_N and y, matrices that represent two presumably-unrelated pieces of the see-saw picture, the right-hand side of Eq. (1) is not real. Then the left-hand side must not be real either. Since M_ν is real, this implies that U is not real. But then, given the well-known relation between light-neutrino oscillation and complex phases in U, one expects that this oscillation will violate CP.

With only a minor caveat, one can reverse this argument: If light-neutrino oscillation violates CP, then, assuming the see-saw picture, leptogenesis probably occurred. We conclude that, generically, leptogenesis and light-neutrino CP violation imply each other.

To be sure, it can be shown that if all the N_i masses exceed 10^{12} GeV, then the phases that drive leptogenesis are independent of those in U [2]. However, there is no need for the N_i masses to be this large. Indeed, supersymmetry suggests that the mass of the lightest N_i must be $\sim 10^9$ GeV [3]. It has been shown that when the smallest N_i mass is below 10^{12} GeV, CP-violating phases in U, which produce CP violation in light-neutrino oscillation and influence the rate for neutrinoless double beta decay, lead also, barring accidental cancellations, to a baryon-antibaryon asymmetry [4].

In summary, assuming the see-saw picture, leptogenesis and light-neutrino CP violation generically do imply each other.

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ν signals in dark matter detectors

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Solar and atmospheric neutrinos are a well-known background in direct dark matter searches, which will become relevant once these experiments reach the ton scale. Here, we argue that, if there is new physics in the neutrino sector, neutrino signals might already be observable in the present generation of experiments, and the phenomenology will be much richer in future detectors. Consider, for instance, a scenario in which the Standard Model is augmented by the introduction of a very light (< 1 eV) new gauge boson, which we will call the "dark photon" A', and by one or several light sterile neutrino flavors. (The existence of sterile neutrinos is not strictly necessary, but it allows for larger new physics signals than a model with only a dark photon.) We assume that the A' coupling to Standard Model particles is very weak (it could for instance arise through a small kinetic mixing term), but the coupling to sterile neutrinos is sizeable. Thus, dark photon-mediated processes among Standard Model particles are strongly suppressed, whereas the cross sections for sterile neutrino–electron scattering and sterile neutrino–nucleus scattering can be relatively large. Moreover, since A' is very light, these scattering cross sections will be larger if the momentum transfer q in the scattering process is small. (This can be easily understood by recalling that the A' propagator is given by $-ig_{\mu\nu}/q^2$.) On their way to the Earth, some of the solar neutrinos can oscillate into sterile neutrinos, which could then be detected by looking for their scattering on electrons or nuclei. Because of the low-energy enhancement, dark matter detectors are better suited for this than higher-threshold detectors like Borexino or SNO. Note that the neutrino signal can also show seasonal variation induced by the varying Earth–Sun distance L, L-dependent oscillations, Earth matter effects, and possibly direction-dependent detection efficiencies. New physics in the neutrino sector can thus lead to signals very similar to those expected from dark matter, and if a signal is observed, it is important to disentangle these possibilities, for instance by measuring precisely the energy spectrum of events and the modulation pattern. On the positive side, dark matter detectors provide a new tool to constrain or discover new physics in the neutrino sector.

Non-standard neutrino physics can not only affect direct dark matter searches, but also searches for neutrinos from WIMP annihilation in the Sun. In particular, if there are sterile neutrinos, new MSW resonances will exist at high energy, and depending on the model parameters these can lead to a complete conversion of some neutrino flavors into sterile states. Thus, if sterile neutrinos exist, IceCube limits on WIMP annihilation might be weakened. On the other hand, if in the future the annihilation cross section and annihilation channels are precisely measured elsewhere, for instance at the LHC, IceCube can be used to study the properties of sterile neutrinos, using the neutrino flux from WIMP annihilation in the Sun.

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Possible Study of Rare Decays of μ and Kaons and a Neutrino Near Detector with a Liquid Argon "ICARUS"-like Detector

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Introduction

The bubble chamber invented in the early 1950s by Don Glazer was one of the greatest advances in elementary particle physics. Combined with a magnetic field, full reconstruction of events such as the Ω^- was possible. Equally important in the history of the particle physics was the invention by David Nygren of the time projection chamber in the late 1970s for electronic track reconstruction. In this proposal we study the possibility of putting magnetic field on liquid Argon (LAr) time projection chamber (TPC) producing a "bubble chamber that is digitized for event reconstruction.

The CP violation in the Kaon sector also can be studied in such a TPC detector. An intense beam of both neutral and charged Kaons can be directed at the volume of liquid Argon TPC to study the ultra rare decay processes of stopping Kaons. One important rare process $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ has the branching ratio of 1.6×10^{-10}. Another is $K^0_L \rightarrow \pi^0 + \nu + \bar{\nu}$. Our goal is to build a magnetized LAr TPC for detection of these rare processes. Future branching ratio measurements is to aim for the sensitivity to the $\sim10^{-14}$ level. In this proposal we discuss the work to study the use of MRI magnet coils for the study of the rare Kaon decays. We consider important also, the future magnetization of large scale liquid Argon TPC. This could be part of the Intensity Frontier development in the DOE and the NSF.

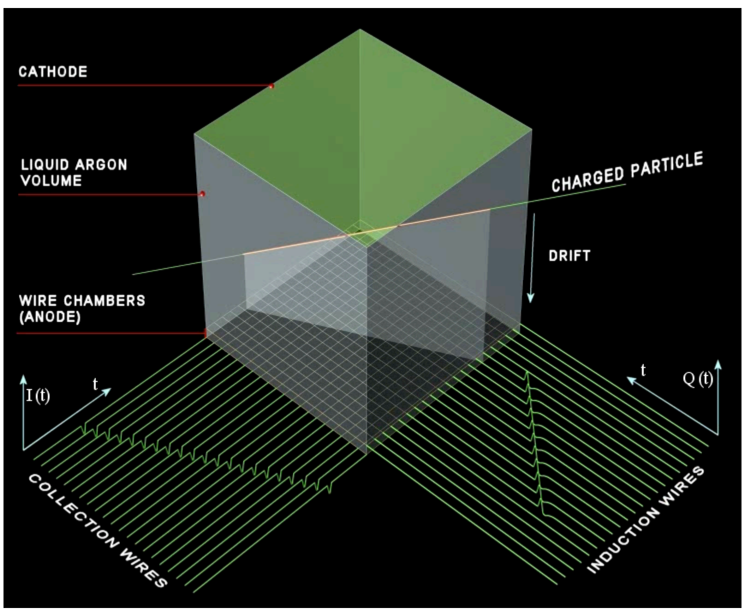


Figure 1. Basic description of the time projection chamber (TPC) with a wire chamber plane at bottom of a cubic cell The wire chamber plane has induction wire plane and a collector wire plane to construct the orthogonal coordinates, and the drift time of the electrons of the ionized track is used to construct the third orthogonal coordinate. The induction wires function as intrinsic signal differentiators and the collector wires as intrinsic signal integrators to be read using charge sensitive preamplifiers and current sensitive preamplifiers respectively [1].

The liquid argon time projection chamber

A massive detector can be built based on the liquid argon TPC technique. Such a technique has been developed and refined within the last two decades by the ICARUS collaboration and demonstrated in the ICARUS-T600 detector currently operating at the Gran Sasso Laboratory for over one year [2]. The LAr

TPC technique is based on an electrified parallelepiped LAr volume with one face occupied by a cathode plane and the opposite face by an anode wire chamber. The electric field E_d of 500 V/cm, in this "instrumented" volume, is maintained extremely uniform by surrounding it with a stack of equally spaced electrodes, set at linearly decreasing voltages from the cathode voltage to ground. Electrons generated by ionizing track crossing the LAr volume drift, under E_d, toward the wire chamber. See Fig. 1.

While approaching, crossing and leaving the first wire plane (wires at 0°) electrons induce a bipolar signal on the wires (*induction* signal). Due to an electric field $E_c \sim 1.5 \cdot E_d$ between the two wire planes, electrons escape the capture by the induction wires and drift toward the second wire plane (wires at 90°) where they are collected (*collection* signal) [1].

Signals generated in the two wire planes and drift time provide the 3-d information on each portion of the ionized track by generating a high definition 3-dimensional imaging of the track. The high definition of reconstructed tracks, together with the possibility of measuring the ionization intensity (*dE/dx*), allows for precise kinematic reconstruction and particle identification.

Description of a magnetized LAr TPC

The electrified parallelepiped volume of the TPC can be magnetized with a strong magnetic field to achieve event charge separation. A singly charged particle with 300 MeV/c momentum requires a 1 T field to deflect with a 1 m bending radius. The E_d field direction can be configured parallel or perpendicular to the *B* field direction depending on the available magnet. A higher resolution is achieved if the track bends in the direction of the TPC drift as in Fig. 2. In the perpendicular configuration, the electron drift velocity of 1.8 m/msec in a 1 T perpendicular field generates a negligible emf, only of 3.6% of the E_d field.

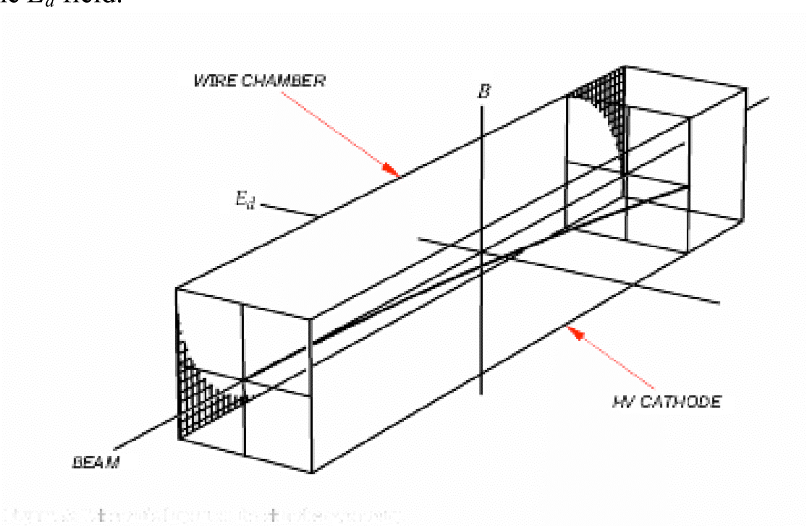


Figure 2. Magnetized TPC volume with the bending plane in the direction of the TPC electron drift, which has a higher position resolution than the wire pitch [1].

The method of magnetizing LAr TPC volume has been tested by A. Rubbia et al. in a small TPC of 15 cm dimensions in 0.55 T field [3]. Measurements of muon events presented in ~2005. For 3σ charge sign discrimination of muons, the B field is at least,

$$B \geq \frac{0.2}{\sqrt{x[m]}}[Tesla],$$

where x is the track length of charged particles. For a magnetic field of 1 T or higher, a track length of only 4 cm is required for charge separation. For momentum measurement, the precision is given as the following,

$$\frac{\Delta p}{p} \approx \frac{0.12}{B[Tesla]\sqrt{x[m]}}$$

where B is the field perpendicular to the motion and x is the track length. For a magnetic field of 1 T and track length of 1 m, the precision is at 12%.

An important application of the magnetized LAr TPC is found in the separation of charge current (CC) interaction of ν_e and $\bar{\nu}_e$ events which produce the electrons and the positrons, particularly for future accelerator based neutrino experiments. In the muon neutrino beam, the dominant component is of the muon neutrinos with smaller numbers of the anti-muon neutrinos and electron neutrinos with each having corresponding energy spectrum. Precision determination at the near detector of the electron neutrino flux and spectrum to a few percent levels is crucial to the measurement of the electron neutrinos at the far detector as well as the energy spectrum. We indicate here only that the MRI magnet with strong field can be used for charge separation in the near detector of the long baseline neutrino experiment.

The ICARUS –T600 detector

With the realization of the T600 detector the ICARUS collaboration finalized a pioneering long term activity on the development of LAr TPCs. The T600 detector is built of two equal sub-modules, each with an active argon volume of 18×3×3.2 m^3 = 168.5 m^3, for a total LAr active mass of 472 Tons. Figure 3 shows the 3-D drawing of the ICARUS detector on left and the actual detector and the cryoplant on right. Figure 4 shows a CNGS high energy neutrino event in the 600 Ton.

The on-surface cosmic-ray test, made in 2001 on the first sub-module, has shown the high definition imaging and calorimetric capabilities of this kind of detector. From reconstruction and analysis of collected events during 3 months many published papers have been produced (see a selection in references 4-14).

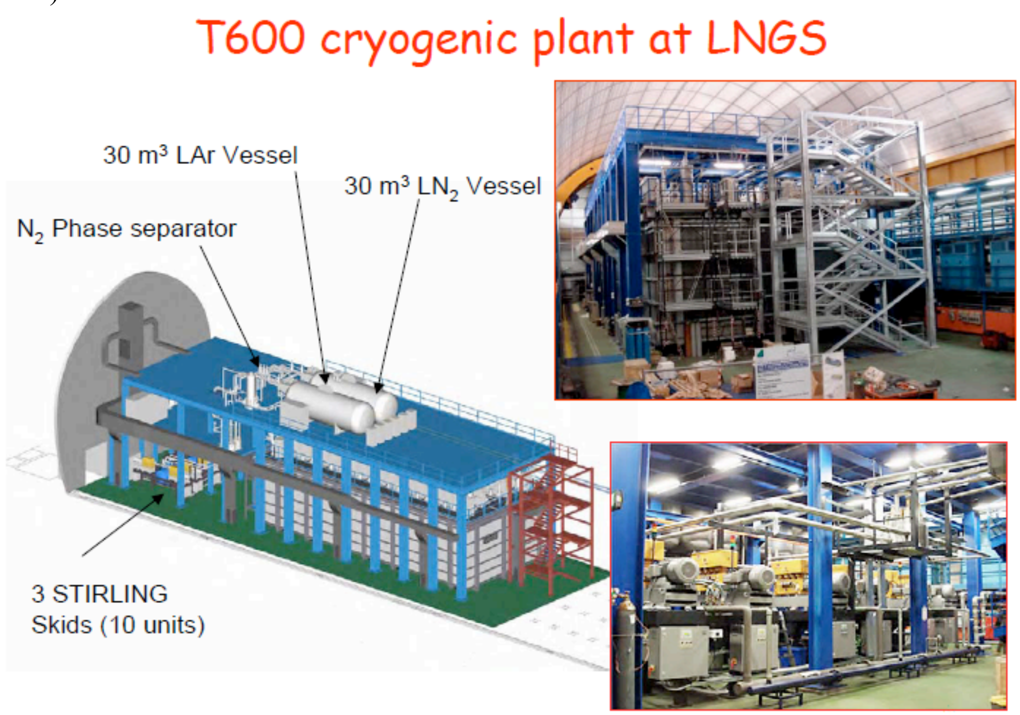


Figure 3. A 3D drawing of the ICARUS-T600 detector with its cryostat plant and photographs of the detector and its service stage in Hall B at Gran Sasso.

The ICARUS-T600 detector started in late May of 2010 the commissioning run in the underground Hall B of the INFN National Gran Sasso Laboratories (Italy). The UCLA group is actively collaborating in this project and took part in its design, test and data analysis of on-surface operation by taking the full responsibility in particular of the design, construction and operation of the T600 high voltage system.

The possible extension of the ICARUS detector to higher masses is planned to be done in the distant future by an array of several equal and independent T600-like modules.

ICARUS–T600 Events

With the recent start of the ICARUS-T600 commissioning run, the new era of high resolution event imaging in neutrino and cosmic ray physics has begun for the high energy particle physics community. Below in Figure 4 is a CNGS neutrino event that have been presented publicly [2]. The TPC detectors can detect tracks per channel at the rate of over ~10^3 Hz. In the ICARUS detector with each wire over a few meters length, signal pulse per wire has a capacitive time constant of ~ 400 nsec. A module of the T-600 twin was operated in early 200 on surface at Pavia in Italy capturing cosmic shower prior to transport to and installation at the Gran Sasso Laboratory. Technically, in this large scale detector with several ten thousand channels, the bottle neck will be at the multiplexing of the wire signals and in the electronics and transfer of the large event data size. UCLA is a member of the ICARUS event scan team.

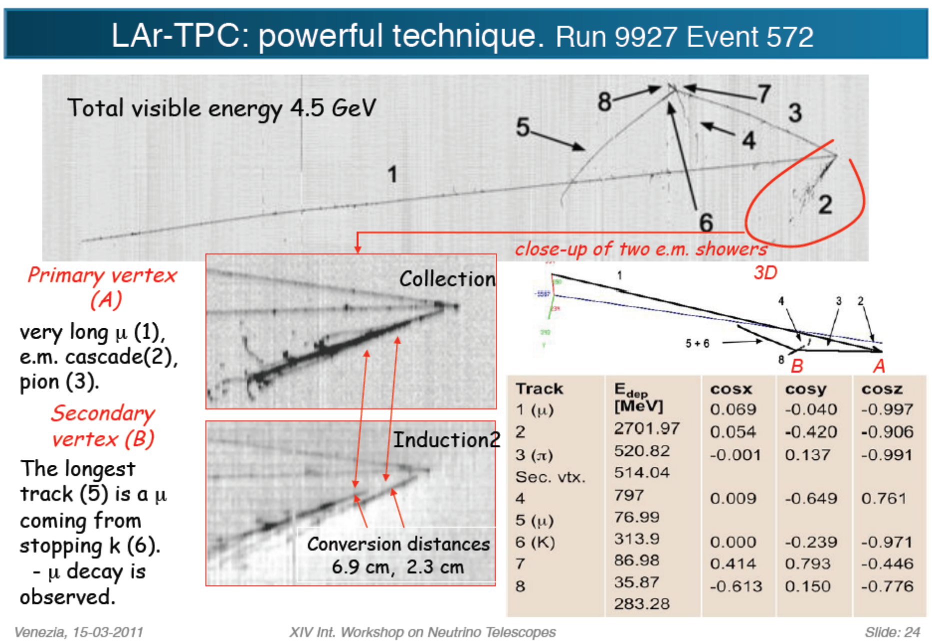


Figure 4. A high energy neutrino event from CERN detected in the ICARUS detector showing long muon track, a pion track and gamma showers[2].

Application to Kaon decay studies

Such a magnetized TPC can be used in the measurement of the rare kaon decay processes for the intensity frontier of the Project X now being developed in the DOE and the NSF. The lifetime of the charged kaons is only ~12.4 nsec while the charged pions 26.0 nsec. The momentum aperture of the beam can be controlled to allow the kaons to “stop” within a certain range of the magnetized TPC volume. The decay products can be measured well by a magnetic field of ~ 1 Tesla strength.

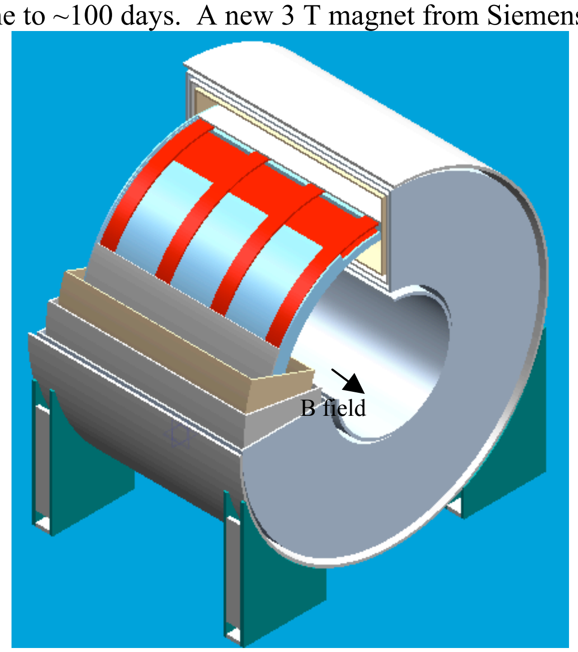
The Project-X is expected to have a very precise timing structure and to deliver ~100 MHz of kaons at the experiment. This requires tremendously fast detector response. The LAr TPC technology while is the best electronic bubble chamber to become operational in the near future, the imaging has a slower response. However, the experiment can be designed to incorporate the high resolution capability and the fast timing response of the Cerenkov light [7] and scintillation light using extremely fast photo-sensors that can operate in the high magnetic field environment. One important characteristic of the TPC is the continuous nature of the scanning that there is almost no dead time, apart from the wire responses. It is expected that there will be about 3 kaons per bunch every 30 to 40 nsec [4]. Also, there will be 1:80 ratio of pions. Due to the very short lifetimes, particle separation can not be achieved by time-of-flight. However, they can be identified by their different ionization track size in the liquid Ar especially when magnetized. Combining a battery of available fast timing information, much of the pion events can be rejected before having to study the associated image.

Magnetized LAr TPC in MRI Magnet

Magnetized LAr TPC has been considered by our group for charge separation of the electron neutrino interaction in one near detector system of the Long Baseline Neutrino Experiment (LBNE). We have considered magnetizing a LAr TPC volume of 2.5 m × 2.5 m × 2.5 m using a cubic coil wound with high temperature superconductor (HTS) wires but operating at ~20 K for cost effectiveness. In this work we will consider the 1.5 T MRI magnet. As many new higher field MRI magnets are becoming available in clinics, one may acquire one of the used magnet in the future phase for this detector development work.

The MRI magnet consists of the liquid He cryostat, the main magnet coil, the gradient coils, and the RF coils [5]. The main coil and some of the gradient coils are located inside the vacuum isolated liquid He reservoir. All currently available MRI magnets are made of low temperature superconducting (LTS) wires. All coils in the MRI magnet that are made of superconducting wires are to operate at the liquid Helium temperature of 4.2 K.

The magnet cryostat consists of the outer shell, the inner He reservoir, the central bore tube and the radiation shields at the two ends. We currently do not have detailed specification of the inner constructs of the cryostat. The inner construction will also vary between various models and manufacturers. For this short length model, the He reservoir can fill to a volume of ~800 liters, a scaled down estimate from the known He volume of 1,500 liter for a ~3 m long magnet. The reservoir is isolated from the outer shell radiation shields and the bore tube by vacuum, achieving good thermal insulation. There are cryo-coolers attached to the top of the outer shell that continuously pump heat out, extending the refill cycle time to ~100 days. A new 3 T magnet from Siemens has zero He boiled off.



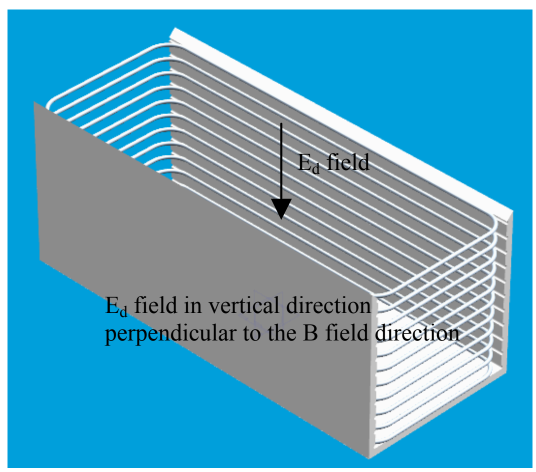


Figure 5. TPC structure is placed in the bore of the MRI magnet cryostat. The drawing shows the cryostat of 1.7 m long and 2.4 m diameter with 0.7 m bore diameter. The TPC structure is of long rectangular rings and PTFE boards with grooves for dielectric insulation. The TPC structure length shown is 1.4 m long. The wire planes not shown are to be of u, v, t configuration with 1 to 2 mm wire pitch for high resolution at top of the TPC structure.

For our application, the bore tube is to be modified into an Ar reservoir for the LAr TPC. The MRI magnets are designed to operate horizontally with symmetric distribution of the structural weight and magnetic forces. We will not attempt to modify any of the stability measures that affect the integrity of the original structural strength. We will design our LAr TPC to fit horizontally in the bore of the MRI magnet. The ends will be modified to allow for vertical tubes extending up from the central bore tube for feed through of the H.V. supply, the cryocooler cold head for the liquid Ar, and the signal wires. All the necessary modifications will conform to providing vacuum isolation for both the He reservoir and the Ar vessel (see Fig. 5).

For fast scanning response, the TPC structure is of rectangular parallelpiped shape to be positioned within the central bore of the MRI magnet. There will be 3 wire planes at top with the u, v, t readout. There will be a strong uniform voltage gradient in the drift direction perpendicular to the MRI magnet field. The TPC will be assembled of rectangular rings at pitch of ~5.1 cm. The H.V. cathode will at the bottom of the structure. The nominal drift voltage gradient is of 500 V/cm. Therefore, for a drift length of 52 cm, the H.V. is of 26 kV. With the extremely high voltages in the device, the H.V. feed through is necessarily well isolated and insulated at all point to prevent electrical discharge to ground. The detector will need to be designed to achieve towards the goal rate of 10^7-10^8 Hz. For rare decay processes this means that at least 10^{15} events/year could be processed.

Rare decay process and summary

The development of a liquid Argon detector in a large magnetic field could open up many particle physics projects. We already discussed a possible detector for $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$. Other rare processes like $\mu^+ \rightarrow e^+ + e^+ + e^-$ could be considered. The excellent charge and vertex identification in a magnetic field could be a key. One might even study CP violating process $K_L \rightarrow \pi^- + \nu + \bar{\nu}$. One might even attempt to measure the extremely rare process $K_L \rightarrow e^+ + e^-$ without any neutrinos in the decay.

The development of a magnetized liquid Argon TPC could have a large future impact. It could lead into also magnetization of much larger volumes in the future long baseline neutrino detectors. While we cannot envision ultra high field of several Tesla in the large neutrino detector, it maybe possible to develop program for magnetization of the entire cavern using superconducting loops with built in cryostats, especially with the recently developed high temperature superconductor (HTS) cable for power transmission. Such idea has been preliminarily studied at the Fermilab.

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Searching for New Particles Beyond the Standard Model by Proton Bremsstrahlung

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1. Theoretical Motivation

Many proposals for new physics beyond the Standard Model (BSM) predict novel, weakly interacting, light scalar or vector particles. Classical examples of such particles include Majorons, axions, Kaluza- Klein modes in the Randall-Sundrum scenarios with extra dimensions and many others. As discussed over the years, novel light particles could be responsible, among other things, for solving the strong CP problem in QCD, giving neutrino its mass, or even explaining the origin of Dark Energy. These new particles can be produced by proton bremsstrahlung and detected by particle decay or scatter in the center of neutrino detectors, assuming that the proton beam is on-axis.

2. Estimated Signal Rates

The model of Nelson and Walsh (Ann E. Nelson and Jonathan Walsh, arXiv:0711.1363) is used to demonstrate the sensitivity of neutrino detectors to new light gauge vector bosons. Nelson and Walsh introduce a new light gauge vector boson ("paraphoton") that is consistent with existing experiments. The paraphoton has a mass of ~ 10 keV, a lifetime of ~ 2.5 ns, and a coupling strength of $g^2/e^2 \sim 10^{-9}$. Such a paraphoton would be produced in the target in the forward direction (< 5 mrad) by hadronic bremsstrahlung of the incident proton beam ($\sim 1\% \times 10^{-9}$) followed by the electromagnetic conversion of the paraphoton in the neutrino detector (total number of radiation lengths, N, times 10^{-9}). Note that the paraphoton would experience hardly any attenuation due to either decay or conversion over the travel distance to the detector. Assuming a reconstruction efficiency of 50%, the number of paraphoton events in the forward direction ($\cos\theta > 0.99$) per 10^{21} POT is approximately equal to

$$(10^{21})(1\%)(10^{-9})(N)(10^{-9})(50\%).$$

Therefore, neutrino detectors should be able to confirm or rule out the model of Nelson and Walsh. Also, new weakly interacting particles could decay in the neutrino detector or contribute to the elastic scattering cross section off electrons. These reactions are also characterized by very forward reconstructed recoil electrons or gammas with $\cos\theta > 0.99$.

BooNE: Upgrading MiniBooNE to Two Detectors

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The MiniBooNE detector began to take data on September 1, 2002. The experiment was designed to search for the appearance of excess electron (anti) neutrinos in a primarily muon (anti) neutrino beam. While resources were not available to construct both a near and far detector at the time, it was envisioned that a second detector would be constructed at a location appropriate to the observed signal if MiniBooNE should see a signal. The second detector would be able to differentiate between a true neutrino oscillation effect and an unforeseen new process or background. A number of scientists now believe that a significant signal has been observed at MiniBooNE, and a collaboration of scientists is forming in order to upgrade MiniBooNE to a two-detector experiment: BooNE.

MiniBooNE has enjoyed a remarkable 9 years of smooth operation, during which an astounding 6×10^{20} protons on target (POT) have been delivered in neutrino mode, and an even more astounding 1×10^{21} POT have been delivered in anti-neutrino mode. The neutrino mode data has yielded a low-energy excess of 129 ± 20(stat) ± 38(sys) events at reconstructed neutrino energies below 475 MeV. That low-energy excess is not described well by a simple two-neutrino model, but can be accommodated by an extended 3 active + 2 sterile neutrino model, fit to the world's relevant neutrino data. While the statistical significance of the low-energy excess is ~ 6σ, the overall significance is limited to ~ 3σ by the systematic error in the estimation of the background, either in the low energy range of 200-475 MeV or in the full range 200-1250 MeV where the excess is 129 ± 20(stat) ± 38(sys) events. That systematic error is related to the error in the detector acceptance or efficiency for π^0 background events, and to a lessor extent, the flux of neutrinos, and the neutrino-nucleus cross sections. Similarly, an excess of is observed in anti-neutrino mode of 54.9 ± 17.4(stat) ± 16.3(sys) events events, consistent with the neutrino-mode data. The anti-neutrino-mode excess is limited in statistical power to ~ 3σ and appears to have a higher energy component of ~ 500-600 MeV.

We now believe we have explored all the possible avenues for explaining the excess events by conventional processes and have exhausted the possible ways to reduce the systematic errors via further analysis. We believe the construction of a near detector at ~ 200 meters from the Booster

Neutrino Beam proton target to be the most expedient way understand whether or not the excess events observed by MiniBooNE are caused by an oscillation process or some other process that scales more conventionally by L^{-2}. The primary motivation for building a near detector, rather than a detector further away, is that the neutrino interaction rate will be over 7 times larger, and the measurement will precisely determine the neutrino-related backgrounds within 6 months of running. A far-detector would take much longer to accumulate sufficient statistics. The combination of the present MiniBooNE neutrino-mode data, plus a 4-month (1×10^{20} POT or ~ 700,000 neutrino events) neutrino-mode run with a near detector, would result in a 5σ sensitivity to whether or not the low energy excess is an oscillation effect. With MiniBooNE's anticipated 1.5×10^{21} POT in antineutrino-mode, BooNE will provide a unique measurement of antineutrino appearance and disappearance with an 8 month run (2×10^{20} POT or ~ 140,000 events) required for comparable statistics.

Furthermore, a two-detector BooNE experiment, in conjunction with the ultra-fine-grained MicroBooNE liquid argon TPC, would be a tremendously powerful, oscillation-hunting combination. While MicroBooNE does not anticipate any antineutrino-mode operation, the operation of BooNE during the MicroBooNE neutrino-mode run would double the statistics of the present MiniBooNE neutrino data to 1.2×10^{21} POT. That powerful trio of detectors would yield precise measurements of *both electron-neutrino appearance and muon neutrino disappearance*, which are tightly coupled in nearly all sterile-neutrino oscillation models.

contribution by: Sanjib Mishra

At the intensity frontier, a very high resolution neutrino detector is proposed with a straw tube tracker (STT) as it its centerpiece. The STT, also serving as an active target with a density of ~0.1 gm/cm^3, is surrounded by 4-pi calorimeter embedded in a dipole magnet with B~0.4 T. Downstream of the magnet and within the magnet-yoke are muon-detectors. Given the unprecedented flux of neutrinos at the intensity frontier, a 4x4x7 m**3 STT will accumulate 100 million NuMu-interactions in 5 years. The detector will fulfill four principal goals:

(a) It will determine the absolute and relative flux of the four neutrino species, NuMu, NuE, NuMuBar, and NuEBar as a function of neutrino energy (Enu);

(b) It will determine the absolute Enu-scale;

(c) It will determine the rate of charged and neutral pion production both in charged current and neutral current interactions, the predominant source of background in oscillation studies.

(d) It will determine neutrino cross sections on water, or on Argon, or on both depending on the constellation of technologies ultimately deployed at the FD site.

An experiment such as this will also provide precision measurements and panoply of physics research at a par with those at the colliders. The LBNE experiment is consider STT as one of the options for near-detector.

1 The Importance of Systematic Errors in the Search/Study of CP-Violation in the Neutrino Sector

With the possibility of larger values of θ_{13}, it has been shown that the importance of systematic errors in establishing CP violations in the neutrino sector is increased significantly since the value of the expected measured asymmetry

$$A_{CP} = \frac{P(\nu_\mu \leftrightarrow \nu_e) - P(\overline{\nu_\mu} \leftrightarrow \overline{\nu_e})}{P(\nu_\mu \leftrightarrow \nu_e) + P(\overline{\nu_\mu} \leftrightarrow \overline{\nu_e})} \tag{1}$$

becomes smaller as θ_{13} increases. This implies that the measured subdominant oscillation probabilities of neutrino and anti-neutrino become more equal and any difference, an indication of CP-violation, can easily be hidden by measurement errors.

A careful determination of the systematic errors for a given experiment is always important and requires considerable effort. To better understand the challenge of determining systematic errors in oscillation experiments consider that the measured signal in our detectors is a convolution of energy-dependent ν flux $\otimes$ energy-dependent cross section $\otimes$ energy-dependent nuclear effects. Specifically for searching for indications of CP-violation, the energy dependence of flux, cross section and nuclear effects are different for ν and $\overline{\nu}$. In addition, since the energy spectrum of the flux entering the far detector is different than the near detector, these convoluted effects do NOT automatically cancel between near and far detectors even if the near and far detectors are made from the same nucleus.

If we assume the systematic errors on the neutrino flux and any detector systematics such as acceptance are determined independently, then a common challenge to all experiments is to determine the systematic errors introduced on the oscillation probabilities by the combined effects of energy-dependent cross section $\otimes$ energy-dependent nuclear effects. The way to unfold these effects in determining, for example, the probability to produce a single π^0 within a given energy band in the final detected state is to choose one of several models for the cross sections for pion production (single and multiple pions and all charge states) on a nucleon and then model the nuclear effects that govern the process including:

- The initial off-shell target nucleon is moving within the nucleus with a given p_N and t_N that can be given, for example, by spectral functions, fermi-gas models or shell-model considerations. Each of these models predict a different probability distribution for p_N and t_N and a systematic uncertainty must be assigned to this step.

- The initial q $\overline{q}$ state can travel through the nucleus before it forms into a strong-interacting meson. This "hadron formation length" has been measured in e/μ - nucleus scattering as a function of the energy-transfer to the nucleus but has a large error that is a systematic error in our measurement.

- once the strong-interacting meson is formed, it is subject to final state interactions that include absorption, charge-exchange scattering, other inelastic scattering phenomena. This is modeled via pion-nucleus data and carries another systematic error.

The process for determining the systematic errors associated with the energy-dependent cross section $\otimes$ energy-dependent nuclear effects has been started in the MINOS experiment and is continuing in more detail with the MINERνA experiment. We are now begining to consider these systematics in more detail for both the IDS-Neutrino Factory and the LBNE experiment and we propose creating a cross-experiment "Systematics Group" to bring all the knowledge and experience of concerned experiments to address this very challenging issue.

Enhancing the low-energy flux in LBNE using a beam created from 8-GeV Protons

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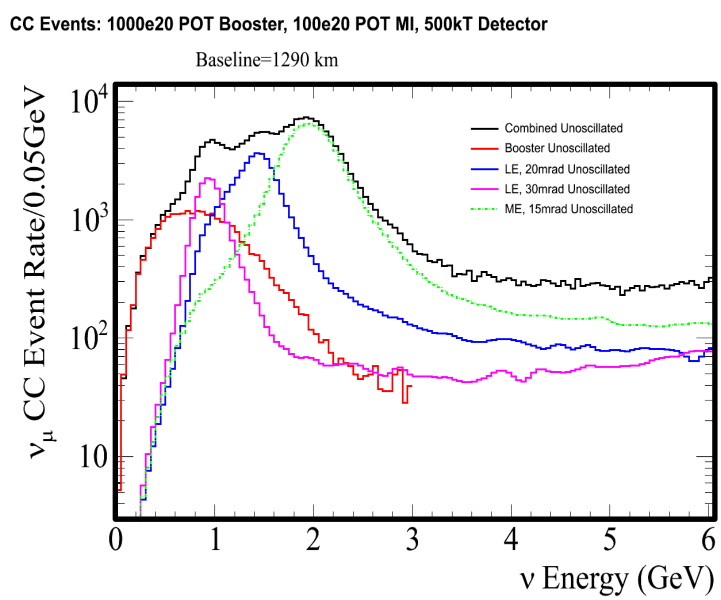
The purpose of this paper is to remind people of a 2005 study on using a future replacement for the booster as a second source of neutrinos for a long baseline experiment. The goal would be to provide additional neutrino flux at low energies to allow for better flux at the second oscillation maximum.

The primary goal for the planned LBNE long-baseline neutrino-oscillation experiment is to explore oscillations in a GeV-range horn-based muon neutrino beam. The LBNE design can use the current Main Injector (MI) and booster complex, but it is primarily envisioned as an experiment that would exploit the full intensity of the Project X accelerator feeding the MI.

The current baseline design for the LBNE neutrino is well optimized for the first oscillation maximum. The real power of the longer LBNE baseline is to exploit the second oscillation maximum too. The differences between the oscillation patterns between the first and second oscillation maximum would allow sensitive studies of the mass hierarchy and the CP violating phase. The LBNE team has worked hard to make a beam design that which maximizes the beam at both oscillation maxima. Their work shows it is hard to achieve a good optimization for both in the same beam line with the same initial proton energy [1].

In 2004, Michael and Smith proposed an experiment based on two primary proton sources targeting the same detector [2]. They proposed that in addition to an MI-based beam targeting the first oscillation maximum that there be a simultaneous second beam produced using 8-GeV protons that would have a peak energy of about 800 MeV, which is well matched to the second oscillation maximum. In simultaneous operation the two beams, with different timing, allow the source of each neutrino to be identified on an event-by-event basis. This significantly reduces backgrounds from neutral current feed down.



The current booster does not produce enough neutrinos to allow a viable experiment. This idea must wait until the Project X era. The lower pion energies in the beam would mean a much shorter, and less expensive decay volume for the lower energy beam. Note that the current Booster Neutrino Beam design is not optimal for a long baseline experiment so a MiniBooNE flux is not an appropriate or optimal assumption. A 2004-era simulation of a flux from 8-GeV protons is plotted in the red in the figure.

Project X has MW power beams of 3-GeV protons and for MI injection. If an upgrade or design change could allow both MI injection and parasitic 8-GeV beams with high power, the low energy beam would have a much better neutrino yield due to better pion production at constant beam power.

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Neutrino-nucleus coherent scattering

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The scientific motivation for measuring neutrino-nucleus coherent scattering is provided in brief below. This measurement is part of the Intensity Frontier because the measurement itself benefits from (perhaps requires) an intense neutrino source.

Reasons to measure the neutrino nucleus coherent scattering cross section:

- Test cross-section prediction from the Standard Model of particle physics
    - The SM provides a clear prediction for the existence of neutrino-nucleus coherent scattering. It has not been experimentally observed. The dominant uncertainties for the cross-section magnitude are, first, the nuclear form factor $F(Q^2)$ and, second, the weak mixing angle via $\sin^2\Theta_W$. At low energies (i.e. $F(Q^2) \sim 1$), measurement of neutrino-nucleus coherent scattering is a 'precision' test of the SM prediction.
    - As a corollary, at higher energies, neutrino-nucleus coherent scattering provides access to measurement of the *neutron* nuclear form factor. [10]
- Magnitude impacts neutrino transport in supernova explosions
    - It is recognized the high intensity production and emission of all flavors of neutrinos plays an important role in the dynamics of supernova explosion. Thus the magnitude of the neutrino-nucleus coherent scattering cross-section significantly contributes to (if not dominates) the total cross section in the energy range of 10-40 MeV for supernova neutrinos as they pass through the explosive envelopes of the supernova. A measurement of the magnitude of the cross-section is an input for future supernova explosion modeling.
- Future detector technologies to measure astrophysical neutrinos
    - Technology developed to measure neutrinos via coherent scattering in a lab-based, terrestrial setting, will provide new techniques for measuring neutrinos in general.
    - Of particular interest are measurements of prompt neutrinos from supernova as well as the diffuse supernova neutrino background. In both cases, the partially neutrino-flavor blind nature of the coherent scattering mechanism is a complement to, for example, large water Cerenkov detectors which are primarily sensitive to electron type neutrinos.
    - *A confluence between the Intensity Frontier and the Cosmic Frontier*
- Relationship between neutrino and WIMP scattering provides a handle on understanding the nature of the WIMP-nucleus nuclear scattering cross-section.
    - The SM predicted model [8] of coherent weak interactions with nuclei is applied to neutrino-nucleus coherent scattering and spin-

independent WIMP-nucleus scattering entirely equivalently. Thus measurement of the neutrino-nucleus coherent scattering at low energies (i.e. $F(Q^2) \sim 1$) provides a point of comparison for WIMP-nucleus scattering. In other words, if the WIMP-nucleus scattering cross-section does not match the neutrino-nucleus coherent scattering cross-section, this is a signature the WIMP-nucleus interaction is 'more complicated'… This interesting outcome should not be unexpected for (as an example) a SUSY particle that is outside of the current SM from which the scattering prediction is formulated.
    - *A confluence between the Intensity Frontier and the Cosmic Frontier*
- Search for non-standard neutrino interactions [6]:
    - For list, see J. Barranco et al., "Sensitivity of low energy neutrino experiments to physics beyond the standard model," Phys. Rev. D 76, 073008 (2007)
    - Unparticle physics tests [7]
    - Existence of a neutrino magnetic moment would also appear
- Ultimate irreducible background to future dark matter detectors
    - A reason to pin-down the magnitude of the cross-section for predicting precisely at what level neutrinos will limit the WIMP cross-section sensitivity of dark matter detectors.
    - See for example write-up by J. Kopp et al. at the Intensity Frontier Neutrino Working Group Workshop on Oct 24, 2011.

A brief view of the experimental program(s):

Three artificial sources are typically considered for the initial measurement of neutrino nucleus coherent scattering:

1. Reactor neutrinos [9]: ($\bar{\nu}_e$)
    - Pro: High flux ($\sim 10^{12}$-10^{13} $\nu/cm^2/s$)
    - Con: Low energy (0-10 MeV, Average energy ~ 3.6 MeV [4])
2. Stopped-pion source [2,3]: (ν_μ , $\bar{\nu}_\mu$, ν_e)
    - Pro: High energy (10-50 MeV; Average Energy ~ 30 MeV)
    - Con: Low flux ($\sim 10^6$-10^7 $\nu/cm^2/s$)
3. Beta beam [5]: ($\bar{\nu}_e$, ν_e)
    - Pro: High energy (10-60 MeV, Average energy ~40 MeV)
    - Con: Low flux ($\sim 10^3$ ν/spill)
    - Con: New facility cost

Proposed measurement methods are:

1. Reactor neutrinos:
    - Germanium ionization spectrometers
    - Liquid argon TPCs

2. Stopped-pion source:
    - Liquid argon or liquid xenon scintillation detectors
    - CsI dectors
3. Beta beams:
    - ?

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Upgrading MINERνA for Future Runs: Challenges for DAQ and Light Yield

Gabriel Perdue on behalf of the MINERνA Collaboration *

October 31, 2011

1 Looking Forward

It is easy to assume that detectors that are around and working now will be around and working forever. This is not a good assumption. Upgrades are required if the MINERνA Experiment is to survive and function as a long-term program beyond its planned physics run during the NOνA Era.

2 MINERνA Readout

The fundamental technologies of MINERνA are: plastic scintillator, wavelength-shifting fiber, and multi-anode PMTs. Readout is conducted using custom Front End Boards (FEBs), custom VME boards, and off-the-shelf rack-mount PCs via a commercial CAEN optical to PCI interface. The FEBs interface with the VME electronics via LVDS using Cat6 ethernet cables.

2.1 Readout Issues

Readout is slow at ∼1 MB/s, but this rate is by design and exceeds the original specification of 100 kB/s on a duty-factor of one 10-μs beam spill every 2.2 seconds. Given the actual event sizes, our rate allows for one physics trigger and one calibration trigger per spill. The bottleneck on readout is due to design choices that create an effectively serial readout. A new interface card will allow parallelization and boost readout rates by a factor of five to ten. This increase should cost approximately $100,000, including design and labor, and is needed for the NOνA era when the Main Injector cycle will change from one spill every 2.2 seconds to one every 1.33 seconds or we will jeopardize data.

*https://neutrino.otterbein.edu/Glaucus/public/list_people.cgi

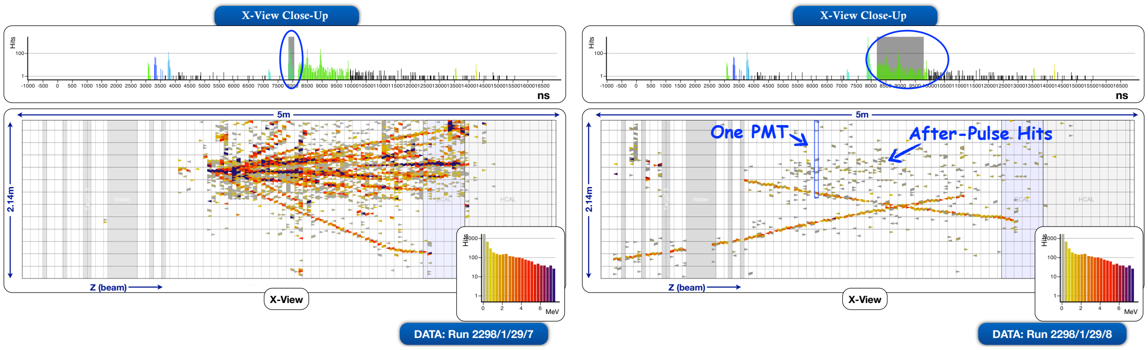

Figure 1: After-pulsing typically occurs after large hits and may generate a sufficient number of "ringing" hits to saturate the readout buffers completely.

The FEBs read 7(+1) hit buffers (the last one is "un-timed" and does not carry hit timing information). Our PMTs after-pulse due to residual gas in the tubes - this wastes hit buffers and introduces avoidable dead-time. See Figure **??** for an illustration.

Additionally, higher intensity or higher energy beam will use more buffers. MINERνA has operated comfortably in the NuMI "Low Energy" mode at 35×10^{12} protons per pulse, but higher intensities and energies may cause problems.

Finally, light yield is a problem. Currently MINERνA operates at approximately 5 p.e./MeV. This somewhat low number is due to the great deal of optical fiber involved in readout leading to high attenuation, but it is within design specifications. However, further drops at a few percent per year (due to scintillator aging) lead to about a 35% loss over a decade which is sufficient to impact timing and tracking resolution.

2.2 Readout Fixes

SiPMs would solve the after-pulsing problem. Those devices are noisy, but the spurious hits are not correlated with pulse height and so are much simpler to calibrate. Would they also solve the hit buffer saturation problem? In other words, are 7(+1) hit buffers sufficient in higher energy configurations with no after-pulsing? We need a study. And a few million dollars for the SiPM upgrade.

SiPMs would also help increase light yield. By removing a large amount of optical fiber from the system, we would gain a $\sim$30% light yield gain.

STERILE NEUTRINOS IN E_6

J. Rosner – Intensity Frontier Workshop – November 30, 2011

Popular grand unified groups: SU(5) $\subset$ SO(10) $\subset$ E_6

Quark and lepton family: $5^* + 10$ of SU(5), no right-handed neutrino

Add a right-handed neutrino N [SU(5) singlet] to get a 16 of SO(10)

10 of SO(10) [5 + 5^* of SU(5)]: L+R quark singlets, lepton doublets

Smallest E_6 rep is 27 containing 16 + 10 + 1 of SO(10)

The 1 of SO(10) is a sterile neutrino "n" with neither L nor R isospin

If grand unified groups are the source of sterile neutrinos (either N or n) then they come in threes.

Neutrino Physics and Astrophysics with IceCube In-fills

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for the PINGU Collaboration

1 Introduction

A conclusive test of many low mass dark matter scenarios, a more precise study of atmospheric oscillation parameters, and an enhanced sensitivity towards supernova burst neutrinos would require a very large neutrino detector with a low energy threshold. Such a detector could be constructed in two phases at the geographic South Pole, making use of the excellent infrastructure, good optical properties of the naturally occurring detector medium and support structure and benefit from the IceCube detector to veto atmospheric muons. A vision to construct a multi-mega-ton ring-imaging ice-cherenkov detector capable of detecting 100 MeV events with numerous scientific applications is described in this document.

2 Path Towards a Large Detector

We propose the construction of a multi-mega-ton ring-imaging detector in two stages. The first stage (PINGU – Phased IceCube Next Generation Upgrade) would consist of an upgrade to the IceCube–DeepCore detector [1] using existing technology complimented with some new optical modules and calibration devices. Physics results are guaranteed by relying on proven IceCube sensors, while the performance of new technologies towards stage 2 can be evaluated. For the first stage 1 we envision the deployment of 18-20 string during two seasons. We aim at achieving an energy threshold of a few GeV for this multi-mega-ton detector.

A stage 2 detector, consisting on the order of 100 strings, using a technology choice based on the performance of the stage 1 array would then aim at constructing a large ring-imaging ice-cherenkov detector. We envision to reconstruct individual events above a threshold on the order of 100MeV and use collective event information to detect supernova burst neutrinos. The targeted detector volume is about five mega-tons with a photo coverage on the order of 10% for the central region of the detector.

3 Physics Motivation

The primary physics driver behind a large ring-imaging ice-cherenkov detector are dark matter searches, neutrino oscillation studies, and increased sensitivity towards supernova burst neutrinos. Extensions reaching proton decay could possibly be contemplated. Other physics topics include, but are not limited to: Sterile neutrinos, Galactic plane neutrinos, neutrinos with soft spectra from Galactic sources, and long-baseline accelerator neutrino oscillation studies [2].

Dark matter scenarios motivated by DAMAs annual modulation signal [3] and isospin-violating scenarios [4] motivated by DAMA and CoGeNT signals could be tested by a mega-ton scale detector with an energy threshold in the GeV range [5].

An energy threshold of a few GeV combined with a good angular and energy resolution, will allow to map out multiple oscillation maxima and minima in the muon neutrino disappearance distribution to perform measurements of Δm^2 and $\sin^2(2\Theta)$. A favorable value of Θ_{13}, as indicated by recent measurements [6], opens up the possibility to determine the neutrino mass hierarchy [7].

A multi-mega-ton detector is necessary to allow for potential detections of supernova burst neutrinos from beyond the Milky Way [8]. Not only would such a detector increase the chances of supernova

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observations, but detections of multiple photons from the same neutrino interaction made possible through a dense sensor spacing potentially allows to reconstruct neutrino burst energy spectra. Besides testing of core-collapse models through the acquired energy spectra and precise timing [9, 10], further science justification lies in the capability to observe neutrinos from collapses that are optically dark and to study neutrino accompanied optically bright events which are not core-collapses.

4 Detector Medium and Technology

The deep ice at the geographic South Pole possesses good optical properties below 2100 m and a high radiopurity. The absorption length at 400 nm is about $\lambda_{\mathrm{abs}} \approx 155$ m and effective scattering length is on the order of $\lambda_{\mathrm{scat}}^{\mathrm{eff}} \approx 47$ m. Uranium (^{238}U) and Thorium (^{232}Th) contaminations are very low at 10^{-4} ppb and Potassium at 0.1 ppb in the Antarctic ice [11]. The combination of low installation costs and the ability to build a contiguous detector not limited in size, makes the South Pole an ideal site. However, the maximum density of instrumentation is determined by the installation procedure and will ultimately determine what photo coverage can be achieved. While the stage 1 detector can rely on the existing hot-water drilling technology, which is well tested for IceCube, for the stage 2 detector there are likely modifications necessary. Nevertheless drilling and deployment costs are expected to be below 10% of the total costs of the array, making the "excavation cost" component a minor one for this array.

IceCube digital optical modules (DOMs) [12] are functioning extremely well, which is undermined by the fact that the number of DOMs that fail commissioning is at a percent level and the number of lost DOMs after successful freeze-in and commissioning is a fraction of a percent. The IceCube detector is operating very stable and shows detector uptimes of about 99%. DeepCore utilizes 252 mm diameter Hamamatsu R7081MOD (super bialkali photocathodes), which are identical to the standard IceCube PMTs (R7081-02), but with a quantum efficiency that is increased 40% at $\lambda = 390$ nm. While, the physics goals of the stage one detector are achievable with the existing DeepCore sensors, we intend to utilize also new photon detection technology, with the goal to demonstrate the potential for reconstructing Cherenkov ring fragments. Developed for KM3NeT [13], multi-PMT optical modules, could be adapted for the use in the ice. A possible design would feature 64 3" PMTs in a cylindrical deployment vessel of similar diameter to an IceCube DOM. The sensor coverage would be the equivalent of approximately two DeepCore 10" PMTs and achieve a pixelization of the detector and a more isotropic light acceptance. Other optical devices utilizing wavelength shifter techniques to increase the photo sensitive area in a cost effective manner are also under consideration.

5 Conclusions

The construction of a large (multi-mega-ton) ring-imaging neutrino detector at the geographic South Pole seems very feasible. A detailed design and physics capabilities study is underway.

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A New Experiment to Verify/Refute the OPERA Result

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1 Introduction

The OPERA Collaboration observed that ν_μ arrived earlier than expected [1]. Interpreted as an anomalous velocity, the neutrinos travel faster than c by 2.48×10^{-5}. This result has caused much discussion and needs to be tested by an independent experiment with different methods. We propose such an experiment.

Our design avoids some of the possible pitfalls of the OPERA analysis. First we use a direct-sight laser to synchronize the primary proton beam and neutrino detector. Second, we build in comparisons to relativistic non-ν particles, mainly muons produced in π/K decays. Third, we allow a minute fraction of the muons to reach the neutrino detector, in order to establish the expected TOF for a relativistic particle with no velocity anomaly. Finally, we take advantage of the time structure of the NuMI beam. Some aspects of our design were used in an earlier experiment by Kalbfleisch *et al.* [2].

The 120 GeV Main Injector beam would be used to collide 120 GeV protons on a target, just as with the NuMI beam. We assume we would take about 500 "batches" each ~ 8 ns long, spaced 18.8 ns apart. We consider 10^{19} or 10^{20} protons on target. The laser is synched to the batches using a non-interfering electrostatic pickup. The decay tube is 10 km long, and 1 m in radius. It is placed on the surface, not underground, to keep costs manageable. It can be filled with Helium gas at low pressure. The detector would collect three kinds of signals: 1) the laser pulses, 2) neutrinos from pion decays, and 3) muons from (other) pion decays. We assume a trasverse position resolution of 1 cm, and a longitudinal resolution of 3 cm. We assume a per-event time resolution of 10 ps, which might be achieved using quartz fibers to collect Cherenkov light from the electromagnetic core of hadronic showers [3].

We used a simple PYTHIA simulation to test our ideas. We modeled the pion production using a 120 GeV p incident on a fixed p, and represented the detector resolution by simple Gaussian smearing. We focussed on the TOF measurement and took the OPERA result as pertaining to the ν velocity: for a 10 km flight distance, the anomaly would correspond to 0.8 ns out of 3.3 μs. Our simulation indicates a yield of about 4×10^{-5} νs per proton passing through a detector 1m$\times$1m in cross section. The mean momentum is about 8 GeV, so the cross section is roughly 4×10^{-38} cm^2. If the detector mass is 24 tons, we would collect about 2×10^4 events for only 10^{19} pot, which is already twice the OPERA sample of contained events.

Figure 1 compares the TOF for muons and neutrinos passing through the target. A clear shift is seen, and even with a few hundred events, zero shift could be ruled out with many sigma.

This concept is under development and this contribution represents initial ideas only.

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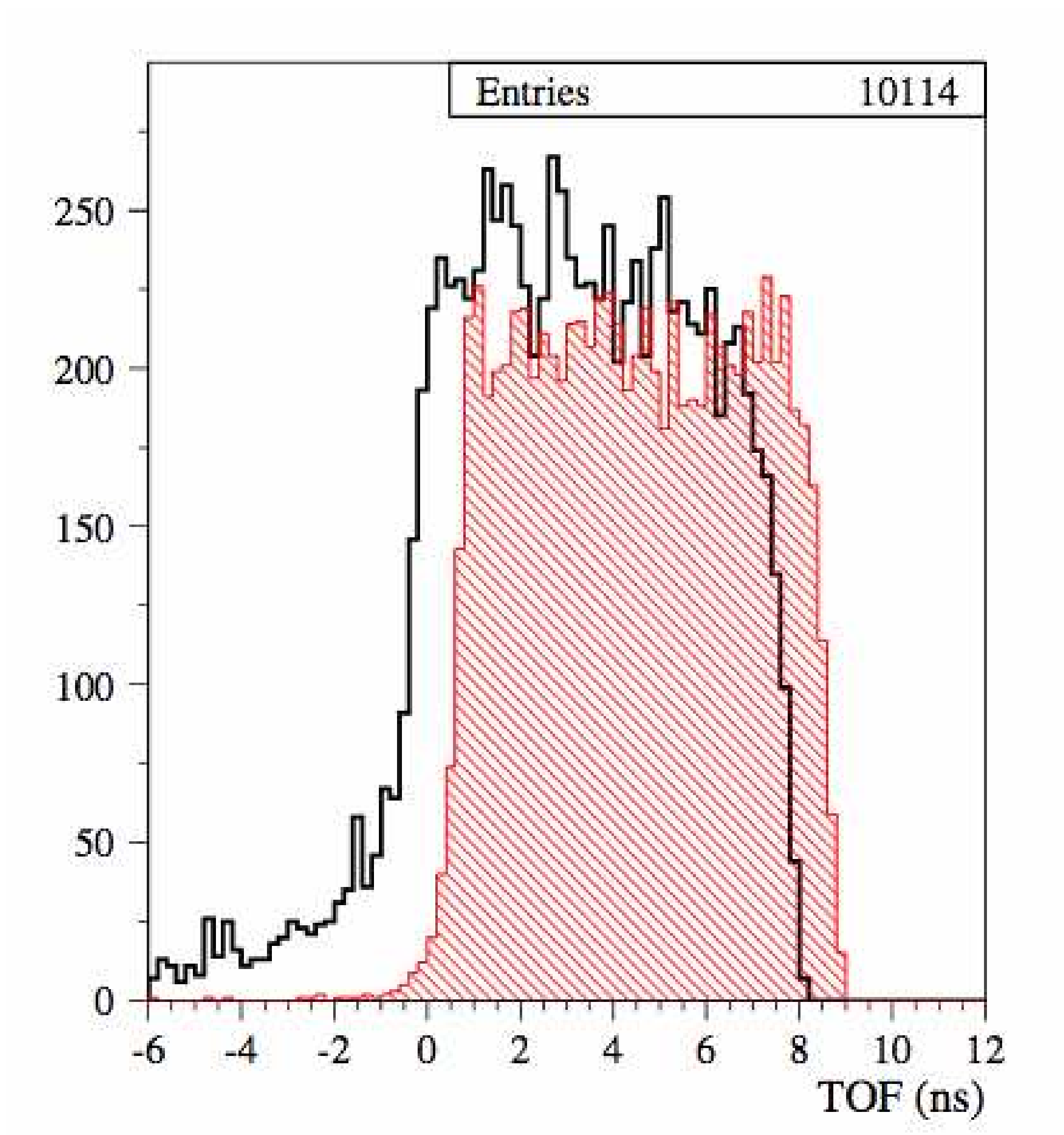

Figure 1: Comparison of the TOF distribution for muons (heavy dark line) and neutrino events (shaded red histogram) assuming that the OPERA ν velocity anomaly is correct.

PINGU receiving accelerator neutrinos

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October 31, 2011

Abstract

This short note explains the basic ideas presented at the Neutrino Working Group Meeting@Fermilab on Oct. 24th, 2011. See the reference [1] in details.

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If one is able to increase the photomultiplier density in the IceCube detector array beyond that of DeepCore, this initiative, known as "Phased IceCube Next Generation Upgrade" (PINGU) detector, would provide an unprecedented fiducial volume with a low energy threshold suitable for accelerator neutrino oscillation experiments.

We study the detector requirements of PINGU for a beta beam, a neutrino factory beam, and a superbeam, where we consider both the case of a small θ_{13}, and that of a large θ_{13}, based on the discovery reach of CP violation, the determination of mass hierarchy and the confirmation of non-zero θ_{13}.

A neutrino beam from one of the major accelerator laboratories in the Northern Hemisphere to such a detector will cross the Earth's core with a distance far beyond the magic baseline, which is often proposed as a second baseline for the neutrino factory or a high γ-beta beam experiment to measure the mass hierarchy and to resolve degeneracies. As a peculiarity, the oscillation probability becomes parameterically enhanced between about 2 and 5 GeV, which means that a large fiducial volume is required in that energy range.

We illustrate that a flavor-clean beta beam best satisfies the requirements of such a detector, in particular, that PINGU may replace a magic baseline detector for small values of θ_{13}; see Fig. 1 (right panel), for the dependence on energy resolution and comparison to the reference beta beam (shaded area: one or two baselines). For a large θ_{13}, however, a single-baseline beta beam experiment cannot compete if it is constrained by the CERN-SPS. For a neutrino factory, without the charge identification possibility in the detector, a very good energy resolution of about $\Delta E = 10\% \, E$ is required. If this can be achieved, especially a low energy neutrino factory, which does not suffer from the tau contamination, may be an interesting option for a large θ_{13}. For the superbeam, where we use the LBNE beam as a reference, electron neutrino flavor identification (with a mis-identification rate of about 1% to 10%) and statistics are two of the main limitations. See Fig. 1 (left panels) for the performance and comparison to the reference setups, if these requirements can be met.

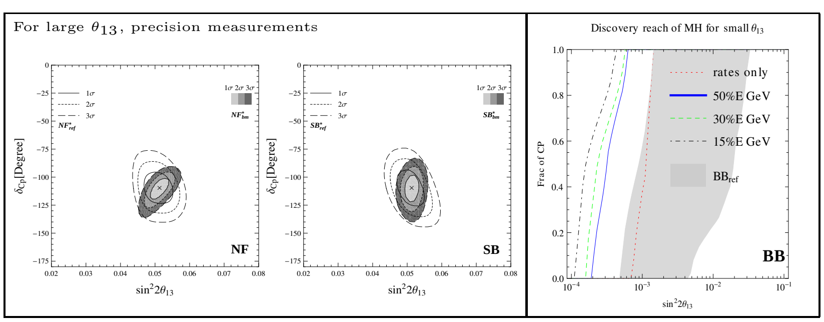

Figure 1: *The shaded region replaces the single baseline with PINGU at the NF and SB, respectively in the left box. Figure taken from Ref. [1].*

A Measurement of Neutrino-Nucleus Scattering in a Narrow-Band Beam: SciNOvA

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November 1, 2011

The discovery of neutrino oscillations has instigated a world-wide experimental effort to use oscillations to measure the fundamental properties of the neutrino. Recent and near-future oscillation experiments in this program such as MiniBooNE, MINOS, T2K, CNGS, NOvA, LBNE, require detailed knowledge of neutrino-nucleus interactions to avoid being limited by uncertainties in the underlying neutrino-nucleus scattering process. Recent data from MiniBooNE and others indicate this knowledge currently eludes us. There currently exists an opportunity for large gains in understanding these interactions via a relatively modest upgrade to the planned NOvA near detector. The resulting measurements would provide crucial neutrino scattering data and would complement that from experiments in other neutrino beams, eg. the SciBooNE and MINERvA experiments.

These other experiments use beams with relatively large energy spread ("wide band") and hence have little a priori knowledge of the incident neutrino energy. NOvA, however, uses a narrow-band neutrino beam centered at 2 GeV. A fine-grained detector in this narrow-band beam would provide a unique opportunity to measure neutrino cross sections with a better constraint on the neutrino energy. In addition, the resulting measurements would provide important cross-checks of estimated backgrounds to oscillations in NOvA.

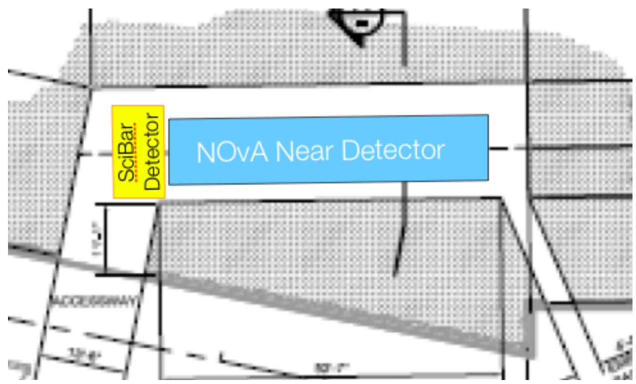

Figure 1: Schematic of the SciBar detector installed in the NOvA cavern just upstream of the NOvA near detector.

The upgrade, "SciNOvA" [1, 2] , requires construction of a SciBar detector as was used in the K2K and SciBooNE experiments, and installing it just upstream of the NOvA near detector underground at Fermilab in the NuMI neutrino beam (Fig. 1. The proposed detector consists of approximately 15,000 scintillator bars of dimensions approximately $1.2 \times 2.4 \times 300$ cm^3 for a total mass of 15tons. Light from the bars is collected with embedded wavelength-shifting optical fibers and routed to a multianode photomultiplier tube for digitization. The estimated cost for this upgrade is $2.4M.

In the region near 2 GeV, this detector would record a large sample of approximately 1 M neutrino events per year simultaneously with the NOvA experiment. This event sample will enable measurements of charged- and neutral-current elastic scattering as well as neutral-current production of pions and photons. These are all important processes in order to precisely measure neutrino oscillations.

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LBNE – in the mean time

Foreward.

The opinions expressed here represent a suggestion of how to move forward, whether or not the funds needed for LBNE are made available. It is, in some sense, a no lose scenario.

Today's Landscape

The neutrino landscape is very quickly changing. The jury is still out about whether θ_{13} really is as large as T2K suggest, but assuming they have not completely underestimated their background, it does look like they have seen appearance of electron neutrinos coming from sub-dominant oscillations of ν_μ. The reactor experiments are about to come on line and should have at least confirmed the very large T2K θ_{13} ($\theta_{13}=10^o$) by early next year (2012).

If θ_{13} really is as large as this then many of the challenges that LBNE is looking to solve can be accessed at the NOVA baseline.

What really are the next Big Questions in neutrino physics? While measuring δcp is academically interesting, it does not lead to leptogenesis. It is an example of how CP violation happens to the left-handed light neutrinos, but it is the $\Delta L=2$ transition of heavy RH Majorana neutrinos which is needed for leptogenesis and the baryon-antibaryon asymmetry of the Universe. The mass hierarchy is more important: it could lead to the confirmation that neutrinos are Dirac particles before the end of the next decade. If the hierarchy is inverted and double beta decay is not seen in the next generation of experiments whose reach should be down to 50 meV, Majorana neutrinos will be ruled out.

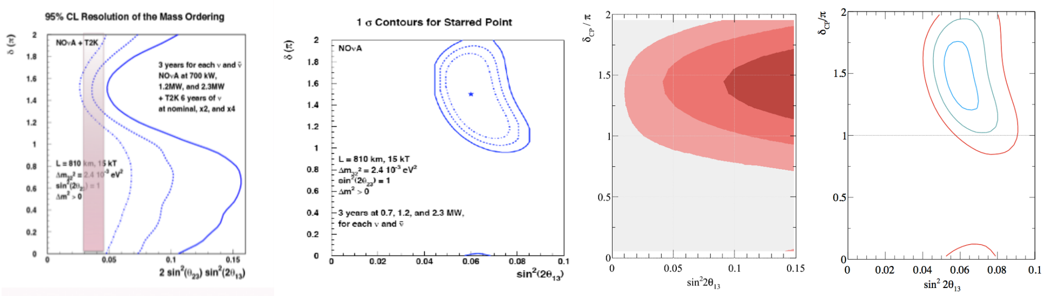
Let us take two scenarios.

A: θ_{13} is moderate: 6^o ($\sin^2 2\theta_{13}=0.043$)

B: θ_{13} is small: 3^o ($\sin^2 2\theta_{13}=0.01$).

Scenario A:

Reactor experiments will take 2-4 years to reach this sensitivity. T2K will come back online, and NOVA will start up. Watching the recent results from T2K shows how fast a well picked baseline experiment can become competitive. By end of 20_{13} there should be evidence from T2K and possibly NOvA that θ_{13} is > 5^o. What is the next thing to do?

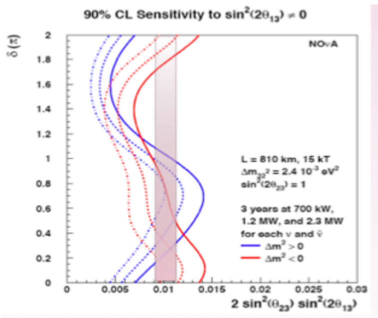


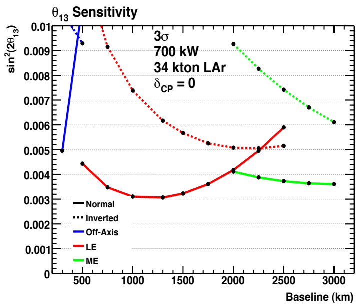
The above figure (far left) shows the status of our knowledge by 2019 combining Nova & T2k wih the reactor experiments. The vertical region is the estimate of how well the reactor experiments would know a θ_{13} at this value (about 10%). The mass hierarchy will not be accessible to NOVA at all unless there were higher beam power or alternatively, more mass. At this θ_{13} there would still be some information to be gained on ruling out some δcp parameter space, but this would not be definitive. Within the next 6 years starting, say, in 2012, it would be possible to augment Nova with 6kT-10kT of LAr. Conservatively, ton for ton, LAr is worth 3x the NOVA mass. This would have several advantages.

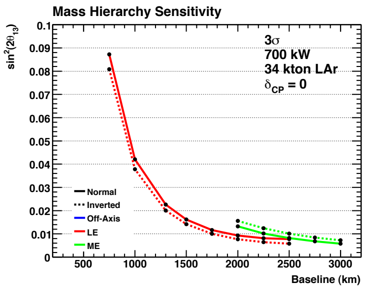
<u>Outcome</u>: By augmenting NOVA with 10kT or LAr, we would know the mass hierarchy, and where to focus on δcp within 10 years. This is shown in the figure above (right) which is a simulation for 14kT of Nova with a 2.3MW beam. This is equivalent to 14kT of Nova and 10kT of LAr with a 700kW beam. Colors are white-red, 1-2,2-3,3-4,4-5 sigma. The plot 2nd from right shows the level of accuracy that δ_{CP} could be measured with if θ_{13} is in the region of 0.04-0.05 (only estimates available)

We need to compare this to where we would be with LBNE in this scenario. It is possible (optimistically) that in 10 years time the cavern is ready and the detector has been built. The new beamline might be ready, and maybe even a year of running is already collected. Nevertheless, it will not have contributed additional information at this juncture.

<u>Scenario B:</u>
Reactor experiments will take 4 or 5 years to reach the sensitivity of 0.01 (or longer) while Nova and T2K will continue to run for a further 2 years (7 years from now) to push down on θ_{13}.







During that 7 years, money could be spent on the development of a higher intensity beam, either at Project-X or at NuMI. Nova + 10kT of LAr with a 1.2MW beam would provide further reach. The figure above center shows the reach of LBNE: but this is just a function of the mass of the detector and the divergence of the beam and is probing the first oscillation peak like Nova, using a LE beam. This is equivalent to augmenting the Nova site with more mass, indeed augmenting NOVA with the full 34kT LAr detector would give NOVA a much extended reach in θ_{13} . The figure above left shows that a large region of δ_{CP} is still undetermined, even with the equivalent of 10kT of LAr in addition to NOVA (equivalent of 2.3MW running). This combination is not systematics limited and more mass and more running will just improve this reach.

<u>Outcome:</u> we would know θ_{13} within 10 years. The plot above right shows the question we would be asking at that point. Where should we put the detector to get at the mass hierarchy? The plot shows that the LE beam gives the best mass hierarchy discrimination, and the result assumes 5+5 years of running. For a 3σ measurement, we might just make it at 2000km but the longer the baseline the further the gain and at this point, more mass or more intensity cannot alone achieve the sensitivity. It is only a longer baseline that can help.

<u>Observations.</u>
Making a decision today on where to put the LBNE is premature and worse, could leave LBNE in the position of doing no better than NOVA could, after a much longer time frame. We could wait to see what θ_{13} is before choosing the baseline. With semi-transportable LAr detectors (there are ships with cryostats that sail around, so this isn't an impossible goal) the baseline could be chosen after the fact rather than before. LAr technology is the new frontier for

neutrino experiments, FNAL has the infrastructure and expertise, and is in a good position to develop the concept of transportable devices to be able to react to short and long baselines alike. There are several different off axis angles which could provide specific information on CP violation, if sites can be found. These studies were done by Rameika et al and can be found in the LBNE DocDB.

Conclusion

I would argue that an adiabatic improvement to the NumI facility and an enlargement of Nova reach using LAr technology will put FNAL in a leading position for the next two decades. It would allow FNAL to take the lead in LAr technology, take the lead in measurement of the mass hierarchy (if θ_{13} is large) , take the lead in θ_{13}measurement (if θ_{13} is small), and to focus on Project –X for delivery of a super high power neutrino beam at some point in the future together with hopefully an array of LAr detectors ready to measure wherever it is pointing.

Measuring the Absolute ν_μ Flux using a Fine-Grain Straw-tube Tracker

Xinchun Tian

November 10, 2011

To conduct precision oscillation physics at the intensity frontier, such as LBNE in Project-X era, is that the ν_μ and $\bar{\nu}_\mu$ charged-current cross-sections be known to $\simeq 3-4\%$ precision. An in-situ determination of the absolute ν_μ flux with a commensurate precision will be highly desirable.

We propose a method of measuring the absolute ν_μ-flux using the ν_μ-e neutral current (NC) scattering. The cross-section of this process is known to be $\simeq 1\%$ precision using the weak-mixing angle measured at the colliders. Thus, if the backgrounds can be drastically reduced and the remaining background constrained, then ν_μ-e NC scattering will provide a means to measure the absolute flux.

The fine-grain straw-tube tracker (STT), currently a candidate for the LBNE near-detector, can accomplish a ν_μ-e NC scattering with $\simeq 3\%$ precision. (See S.R.Mishra's contribution.) The STT is capable of measuring ν_μ-, $\bar{\nu}_\mu$-, ν_e-, and $\bar{\nu}_e$-CC with very high precision. To identify the ν_μ-e NC events, we isolate interactions having a single negative track, require that the track be an electron using the transition-radiation measurements, and finally require that the track be collinear with the incident neutrino, i.e. $\zeta_e = E_e \times (1-\cos\theta_e) < 0.001$. The background, mostly from ν-nucleon NC where the only observable is an e^- from an asymmetric photon decay, is reduced to $< 10^{-5}$ whereas the 64% of the signal survive. Our estimate indicates that with a 700 kW beam and a five year exposure, a sample of > 1500 signal events can be measured with a small, and benign, background.

Measuring coherent-NCνAs at Fermilab

Jonghee Yoo (Fermilab)

The coherent Neutral Current Neutrino Nucleus scattering (coherent-NCνAs) has never been observed since its first theoretical prediction in 1974 by D. Freedman. The condition of coherence requires sufficiently small momentum transfer to the nucleon so that the waves of off-scattered nucleons in the nucleus are all in phase and add up coherently. While interactions of neutrino energy in MeV to GeV-scale will have coherent-NCνAs components, neutrinos with energies less than 50 MeV largely fulfill the coherence condition in most target material with nucleus recoil energy of tens of keV. The elastic neutral current interaction, in particular, leaves no observable signature other than low-energy recoils off the nucleus. Technical difficulties of developing a large scale, low-energy threshold and low-background detector have hampered the experimental realization of the coherent-NCνAs measurement for more than three decades. However, recent innovations in dark matter detector technology have made the unseen coherent-NCνAs testable.

The proposed liquid argon neutrino detector is conceptually similar to dark matter detectors of the similar type. The detector will utilize pulse-shape discrimination of scintillation light between nuclear recoil and electron recoil interactions (and ionization yield) in the liquid argon to identify coherent-NCνAs interactions out of background events. The majority of electromagnetic and neutron backgrounds will be rejected using the standard active and passive shielding methods together with self-shielding fiducialization.

Well-defined neutrino sources are the other essential component to measure coherent-NCνAs. Fermilab has two major neutrino beam-lines; the Neutrinos at the Main Injector (NuMI) and the Booster Neutrino Beam (BNB). The energy range of these two neutrino sources at on-axis is about GeV which is the proper neutrino energy scale to evaluate atmospheric neutrino backgrounds in dark matter searches, where the coherent-NCνAs recoil energy scale is <500 keV. On the other hand, low-energy (<~50 MeV) neutrinos can be obtained through by-product neutrinos at the far-off-axis (> 45 degrees) of the BNB. The BNB source has a substantial advantage over the NuMI beam source owing to the suppressed kaon production from the 8 GeV (8~32 kW) of relatively low-energy proton beam on the target. Therefore, pion-decay and subsequent muon-decay processes are the dominant sources of neutrinos. At the far-off-axis area, the detector can be placed close enough to the target to gain an inverse-distance-squared increase of the neutrino flux. The pulsed structure of the neutrino beam leads to a substantial advantage in background reduction ($\sim 10^{-6}$) against steady-state cosmogenic and radiogenic backgrounds.

The R&D effort would result in a experiment that could go on to make the first observation of coherent-NCνAs; a step forward to comprehend the least understood fundamental particle, the neutrino. The successful experimental results of coherent-NCνAs and associated background measurements in energy range of solar and atmospheric neutrinos will be immediately useful for dark matter search experiments. The far-off-axis neutrino source, incorporated into Fermilab's future Intensity Frontier framework (e.g. Project-X's 8 GeV and 0.3 MW proton beam), may provide a well-defined intensive low-energy neutrino source. Observation of any significant deviation from the predicted neutrino-nucleus scattering amplitude would be an indication of physics beyond the Standard Model. Moreover, the entire sector of dark matter searches will face substantial retreat in the detector sensitivity and will require a new strategy for the next generation dark matter program.

A Novel High Resolution Large-Area Picosecond Photosensor-based Detector

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The next generation of long baseline neutrino and proton decay experiments will use large water detectors which require covering very large surfaces with photo sensors. Traditionally, photomultiplier-tubes (PMTs) have been used as the light detectors useful in low intensity applications. The combination of high gain, low noise, high frequency response, and large area of collection has earned photomultipliers an essential place in nuclear and particle physics, astronomy, medical diagnostics. On the other hand PMTs show limited time and spatial resolution as well as high cost thus limiting high detector coverage which in turn results in less optimized detection performance.

The LAPPD collaboration [1] is developing the planar detector module with 100 pico-second time resolution and one cm spatial resolution across the area of the module. The goal is to develop a commercializable planar detector module. Another new development in the field of the detector R&D is the development of cheap high light-yield water-based liquid scintillator [2]. Using both water Cherenkov radiation with scintillator light could enhance the detection of lower energy particles and particle identification at higher energies. A combination of LAPPD and water-based liquid scintillator detector may lead to applications that could result in game-changing experiments in the field. One possible application of this technology in a longer term that is of particular interest in our field is the proposed Long-Baseline Neutrino Experiment (LBNE) [3].

We propose to design, build and operate a particle detector prototype using, for the first time, the large planar photodetectors (LAPPDs) currently under development at Argonne. The LAPPDs are an advanced alternative to PMTs because of their unprecedented mm-level spatial resolution and better than 100-ps time resolution. Thanks to the reduced cost of these devices one may achieve nearly 100% coverage of a liquid-filled detector (i.e. liquid scintillator (LS), pure water or water-based LS detector). These advances will potentially result in enhanced background rejection and vertex, angular and energy resolution transforming the detection capabilities of future detector technology. In particular, better spatial and timing information will improve vertex and tracking resolution.

Current effort toward a first demonstration of the unique capabilities of this technology is described with the following multi-year approach:

-Characterize and design LAPPD-based detector: simulate and quantify the benefits of a precise position and time resolution, understand particle ID and background rejection capabilities. Explore the advantages and trade-offs of the diverse liquid options: liquid scintillator (LS), pure water or water-based LS detector for small detector applications. We will modify the existing simulation for LBNE to use the small detector prototype geometry. In order to do the liquid comparison, the scintillation component model will be added using experience gained in the MiniBoone and Double Chooz experiments. We will provide input to the LAPPD collaboration on the requirements for prototype modules in this application.

-Begin building a prototype of LAPPD based detector with modules available: design the liquid and photo-detector containment vessel (cylindrical or rectangular geometries are possible), understand the LAPPD module/liquid interface and design the readout scheme.

-Application and operation of LAPPD in LS, water, or water-based LS detector: data analysis and comparison with expectation. Initial testing/operation will be done using cosmic rays. The tracking capabilities and spatial resolution can be demonstrated comparing to a simulated cosmic ray flux. After a successful demonstration with cosmic rays, we will request time at a FNAL test beam using electrons and muons to test the detectors capabilities for electromagnetic showers.

-Operation of a multi kton sized detector in the Booster neutrino beam at Fermilab.

Implementing a first demonstration of the unique capabilities of this technology will impact the rapid adoption in the wide range of fields where photomultipliers are used today.

In summary, the technology of this Novel High Resolution Large-Area Picosecond Photosensor-based Detector has the potential to significantly improve detection performance by increasing the detector coverage, granularity, timing resolution and quantum efficiency and/or reduce the cost of technology. Improved performance would translate into the benefits of a precise position and time resolution when particle interactions are detected, improving particle identification techniques and enhancing background rejection capabilities. The addition of a scintillation component will expand the capabilities of these detectors to low energy particles and further improvements to particle identification at high energies.

[1] http://psec.uchicago.edu/ (Large-Area Picosecond Photo-Detectors Project).

[2] Minfang Yeh, "Water-based Liquid Scintillator", ANT2010-Workshop on Advances in Neutrino Technology, Santa Fe, September 2010; Minfang Yeh, "Water-based Liquid Scintillator for Large-Scale Physics", Argonne High Eneregy Physics Seminar, February 2011.

[3] http://lbne.fnal.gov/ (Long-Baseline Neutrino Experiment).