PXPS12: 2012 Project X Physics Study: Neutrino Detectors Working Group Summary

Conveners: K. McFarland, R. Tayloe, J. Yoo
Contributors: K. Scholberg, J. Spitz, H. Ray, R. Imlay, J. Park, M, Yeh, F. Cavanna, F. DeJongh

July 16, 2012

Abstract

We summarize here the activities of the Neutrino detector working group during the 14-23 June, 2012 Project X Physics Study (PXPS12). In addition, we describe a roadmap for related conceptual design activities and detector R&D.

1 Overview

During the 14-23 June, 2012 Project X Physics Study (PXPS12) held at Fermilab, the Neutrino detectors working group coordinated closely with the Neutrino experiments working group and focused on non-oscillation neutrino physics, searches for beyond-Standard-Model effects, and the detector technologies required for neutrino physics in the Project-X era.

There was significant overlap with other working groups and many workshop sessions were held jointly There were approximately 12 speakers invited by this working group on the topics mentioned above. In the next two sections we summarize the physics and associated equipment detector ideas presented by the speakers and discussed among the participants. In the final section, we offer a roadmap for groundwork required to be ready to do experiments for the various Project X stages.

2 Physics

The physics addressed by this working group consists of supernovae detection and "neutrino-interaction" physics, categorized by the energy of the incident neutrino. As a separate topic, we discussed $\nu - e$ elastic scattering which is relevant for flux normalization, searches for a neutrino magnetic moment, and a measurement of $\sin^2\theta_{\mathrm{w}}$. The final physics topic addressed was searching for dark sector particles via an intense proton source.

2.1 Low-energy neutrino physics

"Low-energy" neutrino physics as categorized here is that done with $E_\nu \approx 50$ MeV as may be produced with a pion decay-at-rest (DAR) beam. Project X, with the construction of MW-class 1 and 3 GeV proton linacs and an appropriate production target, can contribute significantly.

2.1.1 Supernova neutrino physics

There are two possible intersections of supernova neutrinos and Project X: first, assuming that they can be sited underground, most of the large detectors envisioned as a targets for long-baseline neutrino beams offer also excellent prospects for the detection of supernova neutrinos. Second, pion DAR neutrino source built as part of a Project X program would offer excellent opportunities for measurement of neutrino-nucleus interaction cross sections relevant for supernova neutrino physics.

A core collapse supernova will produce a burst of neutrinos of all flavors with energies in the few tens of MeV range. Because of their weak interactions, the neutrinos are able to escape on a timescale of a few tens of seconds after core collapse (the promptness enabling a supernova early warning for astronomers). An initial sharp "neutronization burst" of ν_e (representing about 1% of the total signal) is expected at the outset, from $p + e^- \to n + \nu_e$. Subsequent neutrino flux comes from NC $\nu\bar{\nu}$ pair production. Electron neutrinos have the most interactions with the proto-neutron star core; $\bar{\nu}_e$ have fewer, because neutrons dominate in the core; ν_μ and ν_τ have yet fewer, since NC interactions dominate for these. The fewer the interactions, the deeper inside the proto-neutron star the neutrinos decouple; and the deeper, the hotter. So one expects generally a flavor-energy hierarchy, $\langle E_{\nu_{\mu,\tau}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$ (see Fig. 1).

Despite enormous recent progress, much about the physics of core collapse is not well understood. The neutrino messengers from deep inside the supernova will help us understand many aspects of the supernova mechanism and associated phenomena. The neutrinos are probably intimately involved with the explosion mechanism; imprinted on the flux will be signatures of shock waves, accretion, cooling, possible formation of exotic matter, and further collapse to a black hole, and an improved understanding of supernova nucleosynthesis will result from a detection. The supernova neutrino fluxes will also bring information about the physics of neutrinos themselves. Neutrino oscillations can strongly affect the neutrino fluxes. Matter oscillation effects that come into play as the neutrinos traverse dense stellar matter leave imprints on the spectra.

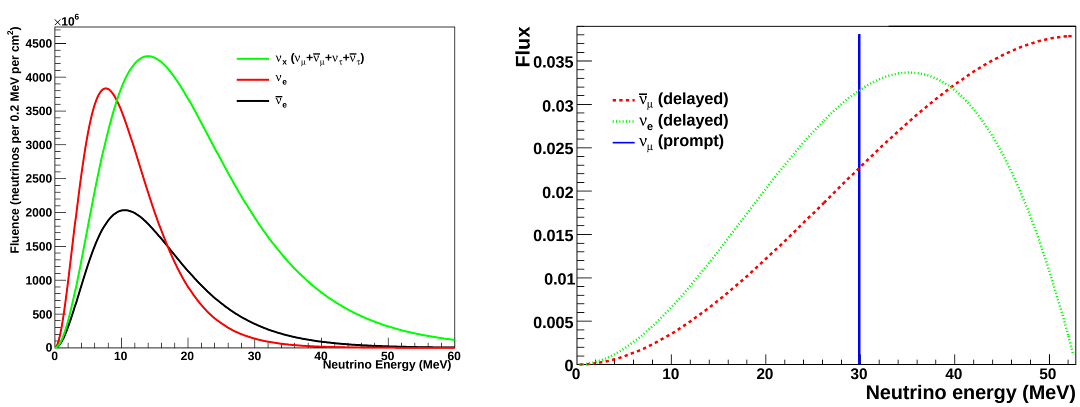

Figure 1: Left: Typical supernova spectrum. Right: Stopped-pion neutrino spectrum.

A stopped-pion source provides monochromatic 30 MeV ν_μ from pion decay at rest, followed on a 2.2 μs timescale by $\bar{\nu}_\mu$ and ν_e with a few tens of MeV from μ decay. The ν spectrum matches the expected supernova spectrum reasonably well (see Fig. 1). A $\sim$ GeV, high-intensity, short-pulse-width, high-duty-cycle proton beam is desirable for creating such a ν source. Prior examples used for neutrino physics include LANSCE and ISIS.

A rich program of physics is possible with such a stopped-pion ν source, including measurement of ν-nucleus cross sections in the few tens of MeV range in a variety of targets relevant for supernova neutrino physics. This territory is almost completely unexplored: so far only ^{12}C has been measured at the 10% level. Understanding of ν-nucleus interactions in this regime is vital for understanding of supernovae: core-collapse dynamics and supernova nucleosynthesis are highly sensitive to ν

processes.

2.1.2 Coherent neutrino nucleus elastic scattering

An intense beam of GeV-scale protons provides an immense opportunity for kaon, pion, and muon DAR experiments. Such a source would allow the first detection of and subsequent high statistics sampling of coherent neutrino nucleus scattering events. Although the process is well predicted by the standard model and has a comparatively large cross section (10^{-39}cm^2) in the relevant energy region ($0 \sim 50$ MeV), neutral current coherent scattering has never been observed before as the low energy nuclear recoil signature is difficult to observe.

A modest sample of a few hundred events collected with a keV-scale-sensitive dark matter style detector could improve upon existing non standard neutrino interaction parameter sensitivities by an order of magnitude or more. A deviation from the $\sim$5% predicted cross section could be an indication of new physics. Either way, the cross section is relevant for understanding the evolution of core collapse supernovae as well as characterizing future burst supernova neutrino events collected with terrestrial detectors.

Well-defined neutrino sources are an essential component to measure coherent-NCAs. There is a unique R&D opportunity to utilize the 8 GeV proton source. According to a recent MC study, the Fermilab Booster Neutrino Beam is potentially a very good source of DAR neutrinos at the far off-axis ($> 45°$) of the beamline. At the far-off-axis area ($> 45°$), 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 (1×10^{-5}) against steady-state cosmogenic and radiogenic backgrounds.

2.2 Intermediate-energy neutrino physics

Our classification of "intermediate-energy" neutrino physics consists of measurements using neutrinos of energy $0.1 \lesssim E_\nu \lesssim 2.0$ GeV such as those available from a pion DIF beam as exists now at Fermilab from the 8 GeV Booster source or the 120 GeV NuMI source. Project X can enable these measurements by providing more POT to these existing neutrino production sources or a new DIF source may be constructed using 8, 60, 120, and (perhaps) 3 GeV intense proton beams.

This area of neutrino physics has been pushed along in the last 10 years by the MiniBooNE, NoMAD, and near-K2K experiments. Ongoing investigations are being performed by MiniBooNE, MINERvA, and T2K. Future work will be required to improve the precision of the results and resolve issues that may be inaccessible with the current experiments. It is important to note that understanding this physics is important both for the fundamental physics it illuminates as well as the required quantities it provides to the neutrino oscillation program.

One of the most notable results coming from this work was the observation that the measured neutrino cross sections on light nuclei (carbon, oxygen) for both charged- and neutral-current processes at $E_\nu \approx 1$ GeV are significantly larger that expected from the state-of-the-art models circa 2000. This was first hinted at in K2K experiment and measured more thoroughly with MiniBooNE. The situation can be seen in Fig. 2 where the data published by MiniBooNE as significantly higher than a model guided by data collected on nucleon targets. That model is also consistent with the NOMAD experiment at higher energies.

The current view of the community is that multinucleon effects within carbon is responsible for this excess in cross section above single nucleon predictions. This will be checked by MINERvA in near future, however if nuclear effects are indeed responsible, a systematic program of measurements into the Project X era will be required to understand the physics across energy and various nuclei.

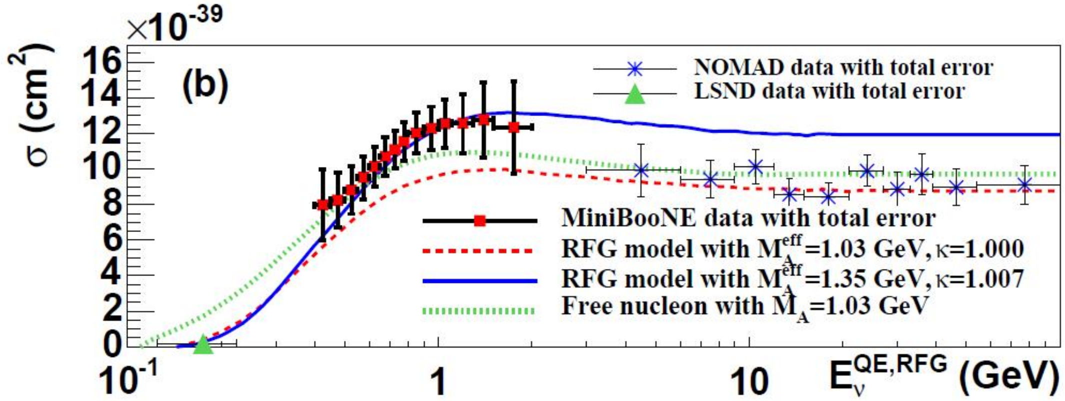

Figure 2: Neutrino-Carbon charged-current quasielastic scattering cross section measured as a function of energy by the MiniBooNE experiment.

In addition to this important issue there are other topics in this energy region likely to require work in the project X era. Some of those are: strange-spin of nucleon (Δs) via NC elastic scattering and coherent production of pions and photons from nuclei.

2.3 Higher-energy neutrino physics

The "higher-energy" category of neutrino physics contains measurement made with $E_\nu \gtrsim 2.0$ GeV neutrino beams such as the current NuMI beam. Project X will allow further work in this regime by provided more POT in the 60, 120 proton energy regime.

The MINERvA experiment is currently working on this neutrino deep-inelastic scattering (DIS) physics with focus on relative and absolute cross section measurements, structure function extraction and the behavior of these quantities as the nucleus is changed.

In the Project X era, the challenge will be to improve the precision of these measurements. In order to do that, higher precision detectors will be required along with more intense better-known neutrino beams. One of the more important limitations of current measurements with the NuMI beam is the uncertainty on the absolute flux. To make the jump in precision desired for this DIS physics, a new type of beam, not utilizing pion DIF, is required. One solution for that is a neutrino factory where a well-known beam of muons decay yielding a intense well-understood neutrino flux. It may be that a big step in this direction can be possible with Project X and a muon DIF beam (such as the nuSTORM project).

2.4 $\nu_\mu - e$ elastic scattering measurements

High statistics samples of neutrino-electron scattering events can be used to (1) search for the ν_μ magnetic moment, (2) measure the weak mixing angle, $\sin^2\theta_\mathrm{w}$ and (3) provide a calibration of the neutrino flux. These measurements may be done at a variety of energies accessible with Project X. However, for the $\sin^2\theta_\mathrm{w}$ measurement, which stands out as the most accessible and important physics topic, the prospect of an intense pion DAR beam at $E_\nu \approx 50$ MeV should be pursued and highest priority.

The present limit on the ν_μ magnetic moment of 6.8×10^{-10} Bohr magnetons is not nearly as good as the limit on the ν_e magnetic moment of 0.5×10^{-10} Bohr magnetons. However, large samples of electron scattering events obtained with DAR or DIF neutrino beams could substantially improve the ν_μ limit, perhaps to the 10^{-10} Bohr magneton level.

Neutrino-electron elastic scattering can provide valuable measurements of the weak mixing angle at various values of Q^2. A well-designed DAR neutrino beam can be used to measure the weak mixing angle at very low Q^2 (≈ 10 MeV^2) with a sensitivity perhaps comparable to that of existing parity violation experiments (0.5%). This would require a proton beam energy around 1 GeV to avoid ν_e from kaon decays, high suppression of neutrinos from the π^-, μ^- decay chain and a short proton beam spill, ideally ≈ 200 ns. The ν_μ from π^+ decays appear promptly while the ν_e and $\bar{\nu}_\mu$ scattering events appear with the muon lifetime. The ratio of prompt to delayed electron scattering events determines $\sin^2\theta_{\rm w}$.

The cross section for electron scattering is very well known and thus elastic scattering can provide an excellent determination of the normalization of the neutrino flux, limited only by the uncertainty of the measurement. The MINERvA experiment is working on using this scattering channel to constrain the NuMI on-axis flux. Current analysis indicates that $\approx 8\%$ statistial error is possible for the NuMI low-energy configuration with improvement to $\approx 3\%$ for the medium-energy.

2.5 Dark sector searches

Battel talk summary here.

3 Future detector development

In order to be build state-of-the-art detectors in the Project X timeframe, it will be necessary to do R&D on detector technologies so that experiments may be ready to deploy them. The following sections summarize the discussion on R&D for scintillation and liquid Argon detectors.

3.1 Scintillation detectors

Liquid scintillator provides neutrino interactions via various detection channels and is an excellent detection medium for neutrinos with $E_\nu \approx 10$ MeV and also up to $E_\nu \approx 1$ GeV if the NC background is well-understood. A large, liquid scintillation detector is known for its multiple physics applications; such as solar, geo, reactor, and supernova neutrino detections short/long baseline neutrino oscillation; and could provide the golden-channel for proton decay via its kaon-capture before decay.

Organic liquid scintillators (LS) have a variety of selections from pseudocumene (PC) to the newly identified, linear alkylbenzene (LAB), which is environmentally safe with high flash point. The physics uses for LS are greatly expanded with the loading of metallic ions of interest; such as triple tags of In-loading for low-energy neutrino spectrum, Te- or Nd-loadings for double-beta decay, or Gd- or Li-loadings for neutron tagging (as antineutrino detection or veto solvent for solid-state or LAr detectors). The synthesis and purification techniques for organometallic-loaded LS (M-LS) have been largely developed (and the R&D for different metallic ions of selections to be loaded in LS has been continuing for different physics of applications). The stability , optical transmission, and photon yield have been demonstrated to meet the critical challenges of experimental requirements by the successful Daya Bay and other reactor experiments.

Here we propose three liquid scintillation systems for future particle-physics experiments that may be executed at Project-X: (1) binary system of pure liquid scintillator mixed with inert solvents, such as mineral oil or dodecane; (2) singular system of pure LS (LAB preferably) with controls of fluor/shifter to potentially preserve the Cerenkov radiation; and (3) the newly developed water-based liquid scintillator, a large, economic detector capable of scintillation and Cerenkov detection.

3.2 Liquid argon TPCs

In the U.S., a precise technology choice for a state-of-the-art fine-grained, high-resolution neutrino detection method has been recently made: *the Liquid Argon Time Projection Chamber* (LArTPC). Current developments on LAr Technology are continuously progressing and actively pursued. These include: electron charge drift over long distance, cryostat insulation schemes and developments, cold read-out electronics vs. warm electronics for signal-to-noise optimization, event reconstruction and off-line code developments, ionization charge signal extraction in alternatives to wires, scintillation light signal extraction, and LAr response characterization with charged-particle beam tests.

The path toward the Intensity Frontier is now addressing the short-baseline anomalies at FNAL, with the MicroBooNE experiment - presently under construction - and with the LAr1 experiment, just proposed to the FNAL-PAC both based on LArTPC detectors.

The MicroBooNE experiment, with a LArTPC of 86 t of active mass (170 t total) is expected to start data taking on the Booster Neutrino beam line at FNAL in 2014, many components are under fabrication (e.g. wire production already completed) and detector construction is being started at FNAL. The superior LAr technology will allow to address the MiniBooNE low-energy excess revealed in neutrino mode with a most efficient e-to-γ separation capability.

In conclusion, the FNAL Program is very rich. A strong effort for the definitive assessment of the LarTPC technology is currently being pursued at FNAL, in particular with the beam test program at the Fermilab Beam Test Facility. The short-baseline program in the short/mid term at FNAL with MicroBooNE, for the definitive clarification of the neutrino-anomaly, and with LAr1 for the anti-neutrino anomaly, has great potential. All this will definitively contribute in opening the way toward the Intensity Frontier neutrino program with Project X.

3.3 Single phase low energy threshold LAr detector

An important aspect of R&D for any of these DAR neutrino measurements is the beam coincident neutron flux which is the most serious background of for these experiment. In order to properly understand the neutron fluxes at the potential experimental sites, an extensive simulation of neutron flux at 20 m away from the target has been carried out. We propose to carry out background estimations of the beam induced neutrons at BNB using 10-kg size of prototype liquid argon detector to measure neutron fluxes in the energy range of the region of interest. Developing a ton-scale ultra-low energy threshold (< 20 keV) neutrino detector is another important R&D subject.

4 Roadmap for Project X

The sections summarized the potential neutrino physics discussed at the PXPS12 workshop under the purview of this working group. In order to build experiments to do this neutrino physics (along with that from the other working groups), a plan will need to be worked out that takes into consideration things such as:

- Timing with other experiments. Which of these physics measurements may be done by the time Project X begins.
- Optimum neutrino source design. How many different sources need to be built. Can one get DIR and DAR sources from same source? Can some of this physics be done with existing sources and more POT or with slight modifications?
- Proton economics. How are protons shared between the different programs and how does that change over time.

- Duty factor. Many, if not all of these experiments will be better done with the low beam-unrelated backgrounds associated with a low duty-factor ($\lesssim 1 \times 10^{-4}$) beam. In that case, either the booster or a storage ring/linac combination would be used.

- Optimal detector design. The sections below lay out the some starting ideas for working through this.

4.1 Conceptual Design

As Project X proceeds through the various stages, the Booster and the Main Injector will still be running and therefore neutrinos may still be delivered from the sources on those machines. As the 1 and 3 GeV linac of Project X, new neutrino targets will be possible, perhaps sharing infrastructure with the targets for muon, neutron, etc production.

The final,staged conceptual design will need to work out a timeline for neutrino source from existing/modified/new production facilities for candidate experiments. This may be done in a clever, economical fashion, but it will take careful design.

4.2 Detector R&D

The detector R&D identified in the PXPS12 workshop required for Project X neutrino projects consisted of:

- New types of liquid scintillator such as LAB and water-based.

- Improvements in segmentation and readout to build large, economical, room-temperature scintillator detectors that can provide more fine-grained and complete information about neutrino interactions.

- Further work with liquid argon TPC detectors to better exploit both the ionization and scintillation and to more efficiently use the wealth of information provided by these detectors.

- Development of ton-scale single phase low-energy threshold liquid argon neutrino detector for coherent scattering measurement

- Various improvements in materials, readout, and analysis in conjunction with topics identified by other working groups with overlapping goals.

4.3 Theoretical Work

In order to support the experimental neutrino physics program and in order to make best use of the results, support of a theoretical program is required. This program will need to address some difficult issues that will require more work over next 5-10 years. In particular, the fairly intricate nuclear physics that arises when interpreting results from neutrino physics experiments that are performed on nuclear targets.