PXPS workshop: nu detectors WG summary

Outline:
- physics
- detector development
- nu source design

R. Tayloe, Indiana U.

2012 Project X Physics Study
June 14 - 23, 2012 • Fermilab • Batavia, Illinois

R. Tayloe, PXPS workshop, 6/12
Neutrino Physics at Project X

- short-, long-baseline oscillations (covered by P. Huber)

- supernova detection

- nu interactions/cross sections
  - "low-energy":
    - $\pi$ DAR source, $\sim$10-50MeV
    - $\nu$ elastic coherent, $\nu N$ supernova interactions
  - "med-energy":
    - $\pi$ DIF source, $\sim$0.1-2.0 GeV
    - 2N correlations, deltas, $\nu$ pi coherent prod, etc
  - "hi-energy":
    - $\pi$ DIF source, $\sim$1.0-10GeV

- nu-e elastic for nu mag moments, sin2thetaw, flux monitoring

- "exotica"
  - dark sector searches
  - non-standard interactions (covered by P. Huber)
Enabling... Neutrino Physics at Project X

Detectors:
- scintillators:
  - new (non-PC mixtures), metal loading, water-based
  - physics techniques with these
  - readout methods, new configurations
- liq-AR (liq noble gases)
  - studies of ionization, light, etc
  - readout techniques, new configs
- others
  - emulsion

nu sources:
- DAR source for ~50MeV nu
  - from 1,3,or 8 GeV
  - target design
  - time structure, buncher ring requirement
- DIF source from 1,3,8,60,120 GeV for 0.5-10GeV nu
  - target design
  - time structure, buncher ring requirement
- DAR kaon source
- "nu-factory" type
Supernova Physics at Project X

- Most large neutrino detectors ($\approx 1kT$) are candidate SN $\nu$ detectors and could provide important info for next supernova event.

What We Can Learn

**CORE COLLAPSE PHYSICS**

- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

**NEUTRINO/OTHER PARTICLE PHYSICS**

- $\nu$ absolute mass (not competitive)
- $\nu$ mixing from spectra: flavor conversion in SN/Earth ('$\theta_{13}$ the lucky and patient way')
- other $\nu$ properties: sterile $\nu$'s, magnetic moment,...
- axions, extra dimensions, FCNC, ...

*+ EARLY ALERT*

Kate Scholberg, Duke University

\(\nu\) detector WG summary  R. Tayloe, PXPS workshop, 6/12
Supernova Physics at Project X
Many detection options exist in detectors of all types...

Table 1: Summary of relevant interactions for current and near-future detectors

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observable(s)(^a)</th>
<th>Interactions(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_e + e^- \rightarrow \nu_e + e^-)</td>
<td>C</td>
<td>17/10</td>
</tr>
<tr>
<td>(\bar{\nu}_e + p \rightarrow e^+ + n)</td>
<td>C, N, A</td>
<td>278/165</td>
</tr>
<tr>
<td>(\nu_x + p \rightarrow \nu_x + p)</td>
<td>C</td>
<td>682/351</td>
</tr>
<tr>
<td>(\nu_x + ^{12}C \rightarrow e^- + ^{12}N(\ast))</td>
<td>C, N, G</td>
<td>3/9</td>
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<tr>
<td>(\bar{\nu}_x + ^{12}C \rightarrow e^+ + ^{12}B(\ast))</td>
<td>C, N, G, A</td>
<td>6/8</td>
</tr>
<tr>
<td>(\nu_x + ^{12}C \rightarrow \nu_x + ^{12}C^\ast)</td>
<td>G, N</td>
<td>68/25</td>
</tr>
<tr>
<td>(\nu_x + ^{16}O \rightarrow e^- + ^{16}P(\ast))</td>
<td>C, N, G</td>
<td>1/4</td>
</tr>
<tr>
<td>(\nu_x + ^{16}O \rightarrow e^+ + ^{16}N(\ast))</td>
<td>C, N, G</td>
<td>7/5</td>
</tr>
<tr>
<td>(\nu_x + ^{16}O \rightarrow \nu_x + ^{16}O^\ast)</td>
<td>G, N</td>
<td>50/12</td>
</tr>
<tr>
<td>(\nu_x + ^{40}Ar \rightarrow e^- + ^{40}K^\ast)</td>
<td>C, G</td>
<td>67/83</td>
</tr>
<tr>
<td>(\bar{\nu}_x + ^{40}Ar \rightarrow e^+ + ^{40}Cl^\ast)</td>
<td>C, A, G</td>
<td>5/4</td>
</tr>
<tr>
<td>(\nu_x + ^{208}Pb \rightarrow e^- + ^{208}Bi^\ast)</td>
<td>N</td>
<td>144/228</td>
</tr>
<tr>
<td>(\nu_x + ^{208}Pb \rightarrow \nu_x + ^{208}Pb^\ast)</td>
<td>N</td>
<td>150/55</td>
</tr>
<tr>
<td>(\nu_x + \Lambda \rightarrow \nu_x + \Lambda)</td>
<td>C</td>
<td>9,408/4,974</td>
</tr>
</tbody>
</table>

\(^a\)Livermore/GKVM

\(^b\)

\(C\): energy loss of a charged particle  
\(N\): neutrons  
\(A\): annihilation gammas  
\(G\): de-excitation gammas

Requires:  
- large detector  
- dedicated triggers  
- (for some channels) calibration in additional experiments...
Neutrino Interaction Physics at Project X

“low-E” (~50MeV) neutrino physics:
- important both for fundamental physics as well as support for oscillations and SN experiments

Neutrino interactions in the few-100 MeV range are relevant for:

- supernova neutrinos
- burst & relic
- solar neutrinos
- low energy atmospheric neutrinos
- oscillation, astrophysics

Kate Scholberg, Duke University
Neutrino Interaction Physics at Project X

CC Low Energy Physics

• CC: $\nu_e, \mu + ^{12}C_{gs} \rightarrow (e^-, \mu^-) + ^{12}N_{gs}$
• CC: $\nu_e, \mu + ^{12}C_{gs} \rightarrow (e^-, \mu^-) + ^{12}N^*$
• CC: anti-$\nu_e + p \rightarrow e^+ + n$

World reactor data, $L \leq 100$ m

H. Ray
Neutrino Interaction Physics at Project X

NC Low Energy Physics

- NC
  - $\nu_x + ^{12}\text{C}_{gs} \rightarrow \nu_x + ^{12}\text{C}^*$, anti-$\nu_x + ^{12}\text{C}_{gs} \rightarrow \text{anti-}$-$\nu_x + ^{12}\text{C}^*$
    - Super-allowed, produces distinctive 15.11 MeV de-excitation photon
    - $\nu_\mu$ only measured by KARMEN, 20% total error, half due to stats
    - Anti-$\nu_\mu$ only measured by KARMEN, 10% total error, half due to stats
    - Sterile neutrino search!!!

  - $\nu_e + e^- \rightarrow e^- + e^-$
    - Precision measurement of $\sin^2 \theta_w$

  - $\nu_x + A \rightarrow \nu_x + A^*$
    - Coherent scattering, imp for SN, never observed due to low recoil E (O tens of keV)

Requires:
- $O(1kt)$ scintillation, liquid noble gas detectors
- $\pi$ DAR source, $O(1\text{MW})$
- low duty factor beam, $<1\text{E-3}$, likely buncher ring required
Neutrino Interaction Physics at Project X

“low-E” (~50MeV) neutrino physics:
- coherent $\nu$ - A elastic scattering

Why is coherent neutrino-nucleus scattering interesting?

- This process has never been detected
- Differences from Standard Model prediction could be a sign of new physics
- Non-standard neutrino interactions
- Supernova process and burst/diffuse neutrino detection
- Weak mixing angle
- Neutron radius
- Sensitivity to sterile neutrino(s)
Neutrino Interaction Physics at Project X

“low-E” (~50MeV) neutrino physics:
- coherent ν - A elastic scattering

Requires:
- O(1ton) liquid noble Argon detector
- π DAR source, O(1MW)
- neutron background mitigation
- low duty factor beam, <1E-3, likely buncher ring required

Coherent neutrino detection at Fermilab

- There is a decay-at-rest neutrino component to the Booster Neutrino Beam, dominating at far-off-axis.
- A WIMP-detector-like single-phase Ar-based device could collect ~200 events/ton/yr at 20 m from the target.

Envisioned experimental setup

Thanks to J. Yoo for plots and information!

Event rate 20 m from BNB target
Neutrino Interaction Physics at Project X

“med-E” (0.1-2GeV) neutrino physics:
- many interesting topics recently addressed by MiniBooNE, SciBooNE
  - multi-nucleon correlations in nuclei

\[ \nu \text{ CCQE total cross section measurement} \]
from MiniBooNE, SciBooNE, NOMAD

- coherent production of pions, photons from nuclei
- “strange”-spin of nucleus, \( \Delta s \)

- Some topics are being addressed by MINERvA, T2K with results appearing now/soon
- However ultimate resolution and understanding across all nuclei likely to require additional experiments in ProjectX era.
Neutrino Interaction Physics at Project X

“med-E” (0.1-2GeV) neutrino physics:
- multi-nucleon correlations in nuclei
- coherent production of pions, photons from nuclei
- “strange”-spin of nucleus, $\Delta s$

Requires:
- scintillator/Cerenkov/liquid Argon detectors
- higher power (100kW) 8GeV DIF source
- possibly 3GeV (1MW) DIF source, lowish duty factor
- H/D targets to disentangle nuclear effects
Neutrino Interaction Physics at Project X

“high-E” (>2GeV) neutrino physics:
- currently being addressed by MINERvA

**Neutrino DIS Motivation**

- Unlike charged lepton scattering, nuclear effects in neutrino scattering have not been directly measured, not well constrained by global fits
- Reasons nuclear effects could be different in neutrino DIS
  - Presence of Axial-Vector current
  - Different nuclear effects for valence and sea quarks, possibly different shadowing for $x_{F_3}$ vs $F_2$?
- Neutrinos have the ability to directly probe the flavor of the nucleon partons
  - $v$ interacts with u-bar, d, c-bar, s, v-bar interacts with u, d-bar, c, s-bar
  - Measuring charm production with $v$, v-bar probes the s, s-bar content within a nucleon
  - $x_{F_3}(v) - x_{F_3}(v\text{-bar}) = 2[(s + s\text{-bar}) - (c + c\text{-bar})]$, information on heavy quark content

- These topics are being addressed by MINERvA, results appearing..
- However more work needed in ProjectX era....
Neutrino Interaction Physics at Project X

“high-E” (>2GeV) neutrino physics:

The DIS Dream

- MINERvAs goal is to know ME flux to 5%
- Can’t investigate the full x range at high $Q^2$

Bjorken $x$:
momentum fraction
carried by the quarks

$$x = \frac{Q^2}{2M_p v}, \quad \nu = E_v - E_\mu$$

Math: for $Q^2 > 1$, $x < 0.1$,
need $E_\nu > 10$ GeV,
$<E_\nu>$ of 20 GeV

- For the future, need detector with excellent acceptance and
energy resolution over full x, $Q^2$ range, know flux to ~1%

Requires:
- high-resolution tracking detectors
- 60-120 GeV DIF source or perhaps “nu-factory” -like source

H. Ray

v detector WG summary
Neutrino Interaction Physics at Project X

nu e elastic scattering:
- neutrino flux calibration
- nu magnetic moment
- weak mixing angle at low Q2

nu \leftrightarrow e elastic scattering:
\nu_{\mu} + e \rightarrow \nu_{\mu} + e
\bar{\nu}_{\mu} + e \rightarrow \bar{\nu}_{\mu} + e

\nu_{\mu} scattering off on light electron has small center of mass energy, so it can have only small momentum transfer, Q^2, which produces very forward electron final state

Well known pure leptonic process is used to get \nu_{\mu} flux information

Small Sample Result

Sample of MINERvA data:
- promising, yet low-stats
- estimate 8.6% stat error on nu e,
- more powerful with MINERvA med-E beam
- higher stats with Project X beams
Neutrino Interaction Physics at Project X

nu e elastic scattering:
- neutrino flux calibration
- nu magnetic moment
- weak mixing angle at low Q2

- Present limit for $\nu_\mu$ is $6.8 \times 10^{-10}$ Bohr Magnetons. LSND PRD 63, 112001
- Present limit for $\nu_e$ is $0.5 \times 10^{-10}$ Bohr Magnetons. Borexino PRL 101, 091302
- At low electron energy, $T_e$, the magnetic moment cross section is given by $d\sigma^M/dT_e = f^2 2.5 \times 10^{-25}$ cm$^2/T_e$ for $T_e << E_e$
  where $f =$ magnetic moment in electron Bohr magnetons
- Because of $1/T_e$ factor want to look at as low an electron energy as possible

- Project X beams will allow improvement on numu limit (to ~$1 \times 10^{-10}$ Bohr magnetons)
Neutrino Interaction Physics at Project X

nu e elastic scattering:
- neutrino flux calibration
- nu magnetic moment
- weak mixing angle at low Q2

• Running with $Q^2$ of $\sin^2\theta_w$.
• Present low $Q^2$ limit ~0.5% from parity violation asymmetry experiment.

- Use Project X π DAR beam

• Get mostly $\nu_e$ and $\bar{\nu}_\mu$ bar from $\mu^+$ decay with 2.2 $\mu$s lifetime and $\nu_\mu$ from $\pi^+$ decay with 26 ns lifetime.
• The ratio $R = \sigma(\nu_\mu e)/[\sigma(\nu_e e) + \sigma(\nu_\mu\text{bar}-e)] = (0.75-3\sin^2\theta_w +4\sin^4\theta_w)/(1+2\sin^2\theta_w +8\sin^4\theta_w)$

Richard Imlay
University of Virginia

PDG 2010

• Measure R to 2-3% for 600 ns spill and $\sin^2\theta_w$ to 1 to 2% in oil or water detector.
• Might do factor of 2 better with 200 ns spill.
Neutrino Interaction Physics at Project X

nu e elastic scattering:
- nu magnetic moment
- weak mixing angle at low Q2

Requires:
- tracking detector
- π DAR source, O(1MW)
- lowish duty factor beam, <10% ?
Dark Sector Physics at Project X

Where are the new particles?

- EWSB, Hierarchy
- Energy Frontier
- Hidden Sector
- Dark Matter

Intensity Frontier

Coupling to SM

Mass of particle (GeV)

Brian Batell
University of Chicago
Dark Sector Physics at Project X

**Dark matter beam**

Dark matter produced in decay of light mediator

\[ \pi_0, \eta \rightarrow \gamma V \]

\[ V \rightarrow \bar{\chi}\chi \]

Neutral current-like event:

\[ \chi e \rightarrow \chi e \]

\[ \chi N \rightarrow \chi N \]

Requires:
- scintillator/Cerenkov/liquid Argon detectors
- higher power (100kW) 8GeV DIF source
Neutrino Detector Development at Project X

Detector development work required for Project X
- scintillators:
  - new (non-PC mixtures), metal loading (n-capture), water-based
  - higher segmentation
  - readout methods, new configurations
- liq-Ar (liq noble gases)
  - studies of ionization, light, etc
  - readout techniques, new configs
- others
  - emulsion
- detector techniques
  - nu beam wrong-sign contribution
  - flux normalization
Neutrino Detector Development at Project X

Detector development work required for Project X
- scintillators:
  - new (non-PC mixtures)
Neutrino Detector Development at Project X

Detector development work required for Project X
- scintillators:
  - metal loading (n-capture), water-based

Option-3: Water-based Liquid Scintillator

- Cost-saving for larger detector (see talk in cost-effective detector session)
- Clean Cerenkov cone with scintillation at few hundreds of photons per MeV (tunable)
- Fast pulse and long attenuation length with minimum ES&H concerns
- A new technology ready to use:
  - Excellent detection medium for proton decay; and other physics
  - Easy to be handled for large detector
  - Gd-soluble
  - A economic large veto solvent

$\bar{\nu}_e + p \rightarrow e^+ + n$

$n + ^{A}\text{Gd} \rightarrow ^{A+1}\text{Gd} + \gamma'$s
Neutrino Detector Development at Project X

Detector development work required for Project X
- scintillators:
  - higher segmentation

scibath detector, Indiana U.
Neutrino Detector Development at Project X

Detector development work required for Project X
- liq-Ar (liq noble gases)
  - studies of ionization, light, etc
  - readout techniques, new configs
Neutrino Detector Development at Project X

Detector development work required for Project X
- others
  - emulsion
Neutrino Detector Development at Project X

Detector development work required for Project X
- detector techiques
  - nu beam wrong-sign contribution
Neutrino Detector Development at Project X

nu sources and parameters to consider:
- DAR source for ~50Mev nu
  - from 1,3,or 8 GeV
  - target design
  - time structure, buncher ring requirement
- DIF source from for 0.5-10GeV nu
  - from 3,8,60,120 GeV
  - target design
  - time structure, buncher ring requirement
- DAR K+ source
- "nu-factory" type
Neutrino Detector Development at Project X

nu sources to consider:
- DAR source for ~50Mev nu
  - competition with SNS, JPARC makes staging important
- from 1,3,or 8 GeV?
  - DAR from 8 GeV may happen earlier, increased 8GeV power can provide incremental gains
  - 1,3 GeV, ~1MW would be world-class DAR source, but will it be timely?
- time structure, buncher ring for ~1E-4 duty factor required for most physics id'd
- target design
  - best if optimized for nu, but may not be crucial
- multiple functions (n-production, etc)

<table>
<thead>
<tr>
<th>Program</th>
<th>MI neutrinos</th>
<th>8 GeV Neutrinos</th>
<th>8 GeV Muon program e.g. (p+e) Mu3e-1</th>
<th>KaoN Program</th>
<th>Nuclear adi ISOL program</th>
<th>Ultra-cold neutron program</th>
<th>Nuclear technology applications</th>
<th># Programs</th>
<th>Total max power</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>470-700 kW**</td>
<td>15 kW + 0-50 kW**</td>
<td>0-20 kWe + 0-50 kW**</td>
<td>0-30 kW**</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>4</td>
<td>735 kW</td>
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<td>515-1200 kW**</td>
<td>0-84 kW**</td>
<td>0-84 kW**</td>
<td>0-75 kW**</td>
<td>0-900 kWe</td>
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<td>0-75 kW**</td>
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<td>0-100 kW</td>
<td>0-100 kW*</td>
<td>0-75 kW**</td>
<td>0-900 kW</td>
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<td>0-1000 kW</td>
<td>8</td>
<td>6492 kW</td>
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<td></td>
<td></td>
<td>0-75 kW**</td>
<td>0-900 kW</td>
<td>0-1000 kW</td>
<td>0-1000 kW</td>
<td>8</td>
<td>11870 kW</td>
</tr>
</tbody>
</table>

* Operating point in range depends on MI energy for neutrinos.
** Operating point in range depends on MI injector slow-spike duty factor (df) for kaon program.
Neutrino Detector Development at Project X

nu sources to consider:
- DAR source for ~50MeV nu

Project X targets

- A chance to design for detector close in?
- 1 MW, 1 GeV
- 1 MHz, 10 nsec beam width
- Can reduce duty cycle only by removing pulses, proportionally reducing power
- If enough motivation to justify expense:
  - Compressor ring
  - Full absorption target
    - More advice from Tennessee colleagues: Target is cheaper if it doesn’t have to be a spallation source.
- As we improve our understanding, we can look at targets being built for other uses and see if any are suitable.
Neutrino Detector Development at Project X

nu sources and parameters to consider:
- DIF source for 0.5-10GeV nu
  - from 3-120 GeV
    - expect much progress pre-projectX from BNB (8GeV), NUMI (120GeV), in NOvA upgrades, LBNE.
    - not clear that new DIF source of same variety called for. from ProjectX
  - new type of DIF source may be needed
  - time structure, buncher ring requirement
    - likely that low-duty factor required
Neutrino Detector Development at Project X

- nu sources:
  - "nu-factory" type (A. Bross)

Well-understood neutrino source:

\[ \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e \]

\[ \mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e \]

- Flavor content fully known
- "Near Absolute" Flux Determination is possible in a storage ring
  - Beam current, polarization, beam divergence monitor, \( \mu_p \) spectrometer
- Overall, there is tremendous control of systematic uncertainties with a well designed system
Neutrino Detector Development at Project X

- nu sources:
  - K+ DAR source?
    - requires >3GeV, intense, proton source.
    - O(10%) duty factor may be ok.
Neutrino Physics at Project X

- short-baseline, long baseline oscillations (covered by P. Huber)

- supernova detection

- nu interactions/cross sections
  - "low-energy":
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Enabling... Neutrino Physics at Project X

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  - "nu-factory" type
Summary

- Project X offers great opportunity for neutrino oscillation, neutrino interaction, non-standard interaction physics.

- Detector R&D work will be required. Planning underway.

- Nu sources from Project X can be world-class. Optimization crucial.