Neutrino Scattering in Liquid Argon TPC Detectors

- What can we learn? Scattering at 1 GeV
- Neutrino Scattering using Liquid Argon TPCS
  - with conventional neutrino beams
  - in Superbeams era
Past neutrino experiments relatively low energy, low statistics bubble chamber experiments

Moved to higher energy experiments higher rates new physics

Rekindled interest in neutrino interaction physics at low energies high flux $\nu$ sources higher precision detectors

within the last decades, neutrino oscillation physics lots of interest moved back to lower energies
Re-kindled Interest in Low Energy Neutrino Cross Sections

- Cross sections at these energies of interest for oscillation physics
- Interesting in their own right

From the APS Neutrino Study:
“Determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino oscillation physics ... Our broad and exacting program of neutrino physics is built upon precise knowledge of how neutrinos interact with matter.”
Ingredients for precision, low energy, neutrino cross section measurements

- High intensity beams $\rightarrow$ high event rates
- Minimize flux uncertainties
  - 15-20% in the past $\rightarrow$ 5% expected by MiniBooNE and less by MINOS/MINERvA
- Minimize background contamination
  - low energy neutrino spectrum (below DIS turn-on and with small high energy tail)
  - fine-grained detector $\rightarrow$ good final state separation

reduced statistical errors

reduced systematic errors
Neutrino beams are moving to lower and lower energies...

<table>
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<tr>
<th>Name</th>
<th>Proton Energy (GeV)</th>
<th>p/yr</th>
<th>Power (MW)</th>
<th>Neutrino Energy (GeV)</th>
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<td>BNL AGS</td>
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<td>0.5-1.3</td>
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Go off-axis for low energy, clean beams

Booster Neutrino Beam at FNAL: similar to T2K off-axis

\( \nu_\mu (\text{RS}) \)
\( \bar{\nu}_\mu (\text{WS}) \)

\( \bar{\nu} \) fluxes have large WS component
Detection techniques: fine-grained, low threshold detectors:

SciBar
- 2cm x 1cm plastic scintillator bars

MINERvA

FINeSSE

Liquid Argon Detectors

T2K 2km LArTPC
Liquid Argon TPC detectors
Readout ionization electrons on wire chamber planes

Arrange E fields and wire spacing for total transparency for induction planes. Final plane collects charge.

Bubble chamber quality with calorimetry and active readout!
Neutrino Scattering at 1 GeV

1) $\nu p \rightarrow \nu p$ elastic scattering to measure $\Delta s$
2) single pion production: unfolding coherent and resonant scattering
3) Search for non-zero neutrino magnetic moments via $\nu e \rightarrow \nu e$ scattering
Neutrinos as Probes

\( \nu p \) Elastic Scattering

(\( \Delta s \): the strange quark contribution to the nucleon spin)

How do the nucleon constituents contribute to the total spin?

(the “proton spin puzzle”)
Valence quarks, sea quarks, gluons?
How does this fit into the fundamental theory of the nucleon?

The neutrino is a uniquely sensitive probe of the strange (sea) quarks in the nucleon.

Neutral-current neutrino-nucleon scattering may be used provide a theoretically robust measurement of \( \Delta s \)

\[
\frac{d\sigma}{dQ^2}(\nu p \rightarrow \nu p) \propto (-G_A + G^s_A)^2
\]

\[G^s_A(Q^2=0)=\Delta s\]

To avoid uncertainties in the flux: Measure ratio

\[
\frac{\nu p \rightarrow \nu p}{\nu n \rightarrow \mu p}
\]
How well can you measure $\Delta s$?

Simulation of $R(NC/CC)$ measurement..

With $\sim 75\text{KNC}$ events and $\sim 180\text{K CQQE}$ events in liquid scintillator detector

Including the effects of:
- statistical errors ( 
- systematic errors due to...
- NCn scattering misid (crucial, recently improved)
- other background channels
- scattering from free protons
- uncertainties in efficiencies
- $Q^2$ reconstruction

experimental (stat + sys) error:

$$\sigma(\Delta s) = \pm 0.025 (\nu), \sigma(\Delta s) = \pm 0.04(\bar{\nu})$$

(previous best measurement from BNL734 $\sigma(\Delta s) = \pm 0.1$)
How well can this measurement be done in LAr?

Neutron ID: Biggest background is from contamination of $\nu_n \rightarrow \nu_n$ in $\nu_p \rightarrow \nu_p$ sample

- Sample of $\nu_p$ and $\nu_n$ events with one proton in the final state
- 86% $\nu_p$ events
- 13% $\nu_n$ events above 100 MeV

in the ball park of how well one can do with scintillator detectors

Laura Jeaney (Yale)
How well can this measurement be done in LAr?
(cont.)

Neutral pion events: Second largest contaminant
   identifiable via topology and dE/dx

Uncertainty in scattering cross section on free protons
   no free protons

Lower energy threshold
   not clear you want to go to lower energies

needs more careful study, but looks like an improvement
Neutral current \( \pi^0 \) production:
biggest background for present and future
\( \nu_\mu \rightarrow \nu_e \) oscillation searches

**No data** below 2 GeV

Lack of data and conflicting predictions → experiments assume 100% uncertainty

need fine-grained detector to distinguish \( \pi^0 \)'s from \( \nu_e \)'s
Both kinematics and rate of $\pi^0$s are not well known... different contributions from resonant and coherent

Comparing $\nu$ vs $\bar{\nu}$ running (FINeSSE flux) extract the forward peaked coherent contribution

These measurements are particularly important for future $\nu_\mu \rightarrow \nu_e$ oscillation searches
CC resonant pion production:
Different isospin content in final state makes neutrino and anti-neutrino interactions distinct...

\[ \nu p \rightarrow \mu p \pi^+ \]

Sensitive beyond \( \Delta(1232) \)
- resonant and non-resonant effects
- interference terms
Electrons versus $\pi^0$'s at 1.5 GeV

Dot indicates hit
color indicates collected charge
green=1 mip, red=2 mips

Multiple secondary tracks
can be traced back to the
same primary vertex

Electrons
Single track (mip scale)
starting from a single vertex

Use both topology and dE/dx to identify interactions
Exotic Neutrino Properties with fine-grained detection at Neutrino Superbeams
Neutrino magnetic moments

massive neutrinos imply existence of $\nu_R$

Expect a non-zero neutrino magnetic moment if you have massive neutrinos

Increase in overall cross section $\sigma_{\text{tot}} = \sigma_{\text{weak}} + \sigma_{\text{EM}}$ Hard to measure with large flux uncertainties
\[
\frac{d\sigma^{\text{weak}}}{dT} = \frac{2m_e G_F^2}{\pi} \left[ g_L^2 + g_R^2 \left( 1 - \frac{T}{E_\nu} \right)^2 - \frac{m_e}{E_\nu} g_R g_L \frac{T}{E_\nu} \right]
\]

\[
\frac{d\sigma^{\text{EM}}}{dT} = \frac{\pi \alpha^2 \mu^2_\nu}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_\nu} \right)
\]

**Shape change in the differential cross section**
Limits set from experiment:

Electron neutrino magnetic moment: -> 1.0 - 1.5 $10^{-10}$ $\mu_B$
- Preliminary measurement from MUNU
- SuperK shape fit

Muon neutrino magnetic moment: -> $6.8 \times 10^{-10}$ $\mu_B$

- LSND experiment: combined measurement of electron and muon neutrino magnetic moment using total $\nu e$ cross section

How is this different from $\nu_e$ searches?

- solar $\nu_e$ measures $\mu_2$ (already set better limits)
- reactor $\bar{\nu}_e$ measures primarily $\mu_1$ and $\mu_2$
- accelerator $\nu_\mu$'s would measure $\mu_1$, $\mu_2$, and $\mu_3$

Tau neutrino magnetic moment: -> $10^{-9}$ $\mu_B$
- SuperK & SNO bounds for all neutrinos
Ingredients for measuring $\mu_{\nu\mu}$ at accelerators:

- Neutrino-electron elastic scattering cross section is low high intensity and relatively large detectors

- Make measurement at low electron recoils where there are lots of radioactive backgrounds

- Need low electron recoil threshold detectors

- Need beam structure to reduce in time background rates

Liquid Argon TPCs!
What happens when you push on electron recoil threshold?

Liquid Argon TPC detectors:
- forward tracks down to 5 MeV
- electron detection down to 150 keV
- energy resolution is about 5% at 5 MeV
- radioactive and spallation backgrounds
  - remove with timing cuts

In Carbon Detectors
- 10 MeV
- 15% at Michel endpoint
Timing is everything!

Radioactive backgrounds become large below 5 MeV uranium, thorium, radon etc.

Even largest bknd ($\gamma$s at 1 MeV) are negligible due to beam timing:

eg: 350 $\gamma$s per year in time with Fermilab's BNB beam spills
Sensitivity study:
Easiest and achievable scenario
15000 events with electron recoil threshold at 5 MeV

An order of magnitude improvement in neutrino magnetic moments

sensitivity: \( \mu_{\nu\mu} = 6.8 \times 10^{-11} \mu_B \)

Significantly better with detection of 150 kev electrons...
LArTPC work underway at Yale

How good are these detectors at IDing low (~1 GeV) energy $\nu$ interactions?

- understand the technology
- purity studies
- understand detector response at very low energies
- study combination of charge and light production for particle ID

Constructing small prototype vessel this summer
Conclusions:

Fine-grained detection techniques are bringing us into the era of precision neutrino scattering physics.

In particular, Liquid Argon TPCs hold promise to improve on all sorts of neutrino scattering measurements and searches for exotic neutrino properties:

- Precision cross section measurements
- Improving measurement of strange spin of the proton
- Extending search for non-zero neutrino magnetic moment