QE or not QE, that is the question

Ornella Palamara
Yale University - INFN, Laboratori Nazionali del Gran Sasso
INT Workshop - Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments
Dec. 3rd 2013 - Seattle
ArgoNeuT

NuMI LE beam

ν̅-mode (2 weeks):
8.5x10^{18} POT

ν̅-mode (5 months):
1.20x10^{20} POT

170 l active volume
47x40x90 cm³, wire spacing 4 mm
LAr TPC

~7000 CC events collected

Largest data sample of [low energy] neutrino interactions in LArTPC

MINOS ND as muon spectrometer

for ArgoNeuT events*

(momentum reconstruction and charge identification (q) of exiting muons)

*ArgoNeuT Coll. is grateful to MINOS Coll. for providing the muon reconstruction
(I) HOW DO YOU SELECT QE EVENTS, I.E., HOW DO YOU DEFINE A QE EVENT?
The “new wave” in Neutrino Event Reconstruction

LAr-TPC detectors, providing *bubble-chamber-like quality images* and *excellent particle ID* and *background rejection*, allow for *MC independent measurements*, *nuclear effects exploration* and *Exclusive Topology recognition* with extraordinary sensitivity.

Instead of MC based classification of the events in the interaction channels (QE, RES, DIS etc), CC neutrino events in LAr can be classified in terms of *Final State Topology* based on Particle Multiplicity:

- **0 pion** (\(\mu+N_p\), where \(N=0,1,2\ldots\))
- **1 pion** (\(\mu+N_p+\pi\)) events, etc..

*Exclusive Topologies reconstruction in LAr-TPC experiments: a Novel Approach for precise Neutrino-Nucleus Cross-Sections Measurements*

(2) HOW DO YOU DETERMINE YOUR NEUTRINO/ANTINEUTRINO FLUX?

NuMI flux: see Nate Mayer talk
(3b) WHAT IS (ARE) YOUR PRIMARY QE MEASUREMENT(S) AND

(3a) WHAT DO YOU FIND MOST IMPORTANT ABOUT YOUR DATA?
(3a) WHAT DO YOU FIND MOST IMPORTANT ABOUT YOUR DATA (I)?

νμ CC 0 pion analysis approach

Count (Pld) and reconstruct protons at the neutrino interaction vertex* (low proton energy threshold)
Analysis fully exploiting LArTPC’s capabilities (in other neutrino detectors all these classes of events are “CCQE like” events)

**Event reconstruction in LArTPC**
* 3D and calorimetric reconstruction for efficient Particle Identification
* Excellent resolution for final state
* Capability of “seeing” recoil proton(s)
* Good p/π± identification capability

*The muon+Np sample can also contain neutrons. The presence of neutrons in the events cannot be measured, since ArgoNeuT volume is too small to have significant chances for n to convert into protons in the LAr volume before escaping.
Note: Due to bubble-chamber like quality of LArTPC, visual scanning presents a very powerful tool that allows to learn about features of neutrino interactions that have not been possible to explore with other technologies and existing experiments.

Hints for Nuclear Effects

Activity around the vertex
e’s from nuclear de-excitation γ conversion

Evidence of Nuclear Effects

µ⁻ 0p

Multi-p accompanying
the leading muon
(many knockout nucleons)

ArgoNeuT events: Single µ⁻ event (Left), Multi-proton event (Right)
Rates of different exclusive topologies (proton multiplicities) with a proton threshold of 21 MeV kinetic energy

Muon and proton kinematics in events with different proton multiplicity

Most precise reconstruction of the incoming neutrino energy from lepton AND proton kinematics.

Features of neutrino interactions and associated Nuclear Effects [e.g. short range NN-correlations inside the nucleus] from identification/reconstruction of specific classes of neutrino events
(4) WHAT ADDITIONAL QE MEASUREMENTS DO YOU HAVE PLANNED FOR THE FUTURE, IF ANY?

- Present results in terms of CC 0 pion cross section
- Extend the study of Nuclear Effects to anti-neutrino events
- Reconstruction of $\mu+Np+1\pi$ events to compare with other experiments
- ArgoNeuT (CC 0 pion) vs. CC QE like results, applying equal threshold on pions.
### characteristics of selected $\nu_\mu$ QE events

<table>
<thead>
<tr>
<th>“QE event” selection</th>
<th>Neutrino events categorized in terms of final state topology based on particle multiplicity rather than in terms of interaction channel: “0-pion&quot; (i.e. $\mu$+Np, where N=0,1,2...) Neutrons can also be emitted in these events: ArgoNeuT has a very low efficiency to detect neutrons emerging from the interaction vertex since the LAr volume is too small to have significant chances for neutrons to convert into visible protons before escaping.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear target</td>
<td>$^{40}\text{Ar}_{18}$</td>
</tr>
<tr>
<td>Sign-selection</td>
<td>Muon sign selection from MINOS-ND</td>
</tr>
<tr>
<td>Muon energy range</td>
<td>Requiring muon sign determination from downstream MINOS-ND: $T_\mu &gt; 400$ MeV</td>
</tr>
<tr>
<td>Muon angular range</td>
<td>About 2$\pi$ forward w.r.t neutrino beam</td>
</tr>
<tr>
<td>Proton detection threshold</td>
<td>Proton reconstruction threshold: $T_p &gt; 21$ MeV</td>
</tr>
<tr>
<td>How is $E_\nu$ determined?</td>
<td>From the lepton AND proton(s) reconstructed kinematics: $E_\nu = (E_\mu + \Sigma T_p + T_x + E_{miss})$</td>
</tr>
<tr>
<td>How is $Q^2$ determined?</td>
<td>$Q^2 = -m_{\mu}^2 + 2E_\nu (E_\nu - p_\mu \cos \theta_\mu)$</td>
</tr>
<tr>
<td>Monte Carlo generator</td>
<td>GENIE 2.8.0 <em>(full simulation)</em>, GIBUU</td>
</tr>
<tr>
<td>QE measurements and associated publications</td>
<td>Rates of different exclusive topologies (proton multiplicities), muon and proton kinematics in events with different proton multiplicity, reconstructed neutrino energy, features of neutrino interactions and associated nuclear effects [e.g. short range NN-correlations inside the nucleus] from identification/reconstruction of specific classes of events</td>
</tr>
</tbody>
</table>
EVENT TOPOLOGY

\[ \mu \rightarrow 1\mu + 0p \]

\[ \mu \rightarrow 1\mu + 1p \]

\[ p \rightarrow 1\mu + 2p \]

\[ p \rightarrow 1\mu + 3p \]

Sensitive to SRC

ArgoNeuT Data

Low charge

High charge

\[ v_{\text{beam}} \rightarrow 1\mu + 1p \]

\[ v_{\text{beam}} \rightarrow 1\mu + 2p \]
Muon kinematic reconstruction:
ArgoNeuT + MINOS ND measurement (momentum and sign)

Muon momentum resolution: 5-10%

“Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector”
JINST 7 P10020 (2012)

Muon kinematic reconstruction:
ArgoNeuT + MINOS ND measurement (momentum and sign)

Muon momentum resolution: 5-10%
Measurement of:
• $dE/dx$ vs. residual range along the track
• kinetic energy vs. track length

$\chi^2$ based method is used for PID
Proton Multiplicity ($\mu+Np$ events)

$\nu_\mu$ - anti-neutrino mode run

$\bar{\nu}_\mu$ - anti-neutrino mode run

ArgonneT data

GENIE

The systematic error band on the MC represent the NuMI flux uncertainty (see N. Mayer talk)

proton threshold: $T_p > 21$ MeV

$\nu_\mu$ events: 50% $N\neq 1$

$\bar{\nu}_\mu$ events: 32% $N\neq 0$

GENIE MC models more higher multiplicity events
MC PREDICTIONS by Physical Process

$\nu_\mu$ - anti-neutrino mode run

- GENIE Total
  - $\nu_\mu$ CCQE
  - $\nu_\mu$ CCRES
  - $\nu_\mu$ CCDIS

$\bar{\nu}_\mu$ - anti-neutrino mode run

- GENIE Total
  - $\bar{\nu}_\mu$ CCQE
  - $\bar{\nu}_\mu$ CCRES
  - $\bar{\nu}_\mu$ CCDIS

The MC generators predict varying amounts of proton emission.

GENIE: ~30% contribution from non-CCQE events
GIBUU: ~50% contribution from non-CCQE events
PROTON KINEMATICS

\( \bar{\nu}_\mu \) - anti-neutrino mode run

\( \nu_\mu \) - anti-neutrino mode run

\[ \langle L \rangle = 3.5 \text{ cm DATA} \]
\[ \langle L \rangle = 5.7 \text{ cm GENIE} \]

\[ \langle L \rangle = 5.6 \text{ cm DATA} \]
\[ \langle L \rangle = 7.7 \text{ cm GENIE} \]

\[ \langle K_E \rangle = 57 \text{ MeV DATA} \]
\[ \langle K_E \rangle = 72 \text{ MeV GENIE} \]

\[ \langle K_E \rangle = 72 \text{ MeV DATA} \]
\[ \langle K_E \rangle = 93 \text{ MeV GENIE} \]

GENIE MC models more energetic protons
Neutrino Energy from muon+proton reconstructed kinematics:
\[ E_\nu = E_\mu + \sum T_{pi} + T_\chi + E_{\text{miss}} \]
- \( E_{\text{miss}} \): energy expended to remove the nucleon(s) from the nucleus
- \( T_\chi \): recoil energy of the residual nuclear system (estimated from missing transverse momentum)

No just muon information

Reconstruction of other kinematic quantity (q, \( Q^2 \), \( p_T^{\text{miss}} \) etc.)
NUCLEON-NUCLEON CORRELATIONS

Two-nucleon knockout from high energy scattering processes is the most appropriate venue to probe NN correlations in nuclei. Two nucleons can be naturally ejected by:

- **Two-body mechanisms:**
  - MEC - two steps interactions probing two nucleons correlated by meson exchange currents, and
  - “Isobar Currents” (IC) - intermediate state Δ excitation of a nucleon in a pair with decay pion reabsorbed by the other nucleon.

The NN-pairs in these two-body processes may or may not be SRC pairs.

- **One-body interactions:** two-nucleon ejection only if the struck nucleon is in a SRC pair, the high relative momentum in the pair would cause the correlated nucleon to recoil and be ejected as well.

- We know (now) that about 20% Nucleons in Nuclei are in SRC (np) pairs

- Long range correlations (MEC) are very relevant and may change significantly XSECT measurements

- Pion absorption (two-body) is relevant

- FSI’s are always a big pain!

- All these effects are combined and interfere w/ each other - (e.g. MEC can involve SRC pairs !)
Search for possible hints of nucleon-nucleon correlations in the ArgoNeuT data, by specifically looking at the neutrino events with $N=2$ protons in final state, i.e. the $(\mu^-+2p)$ triple coincidence topology.

Data sample: 30 events in total (19 collected in the anti-neutrino mode run and 11 in the neutrino mode run).

Both proton tracks are required to be fully contained inside the fiducial volume (FV) of the TPC and above energy threshold. From detector simulation, the overall acceptance for the $(\mu^-+2p)$ sample is estimated to be around 35% (dominated by the containment requirement in FV).

According to GENIE MC simulation: $\sim$40% of these are due to CC QE interactions and about 40% to CC RES pionless interactions.

$(\mu^-+2p)/(\mu^-+Np)=21\%$ (26%) and $(\mu^-+2p)/\text{CC-inclusive}\sim2\%$ ($\sim4\%$) for the anti-neutrino-mode run (neutrino-mode) [efficiency corrected]
Momentum of the more energetic proton \( p_{p1} \) in the pair vs. momentum of the other (less energetic) proton \( p_{p2} \)

Most of the events (19 out of 30) have both protons above Fermi momentum of the Ar nucleus (\( k_F \approx 250 \text{ MeV} \))

\[ \cos(\gamma) \] vs the lower proton momentum in the pair and distribution of \( \cos(\gamma) \) [insert]

\( \gamma = \text{angle in space between the two proton tracks in the Lab reference frame} \)

Four of the 19 2p-events are found with the pair in a back-to-back configuration [\( \cos(\gamma) < -0.95 \), with one p almost exactly balanced by the other \( (\vec{p}_{p1}, \vec{p}_{p2} \geq k_F \text{ and } \vec{p}_{p1} = -\vec{p}_{p2}) \)]

Proton angular resolution: 1-1.5°
Proton energy resolution: ~6% for protons above Fermi momentum
interaction vertex

\[ \nu \text{ beam} \!
\]

\[ p_2 \]

\[ p_1 \]

Proton:

Calorimetric reconstruction and PId

Angle between two protons $\gamma = 178^\circ$

Visually appearing as hammer (muon forming the handle and the back-to-back protons forming the head)

Neutrino interaction producing a back-to-back proton pair

Back-to-back protons

\[ \nu \text{ beam} \!]\]

\[ p_2 \]

\[ p_1 \]

\[ \mu^- \]
Pairs of energetic protons with 3-momentum $p_{p1}, p_{p2} \geq k_F$ detected at large opening angles directly in the Lab frame were observed in bubble-chamber by hadron scattering experiments (pion absorption on nuclei). This was interpreted as hints for SRC in the target nucleus.

Electron scattering experiments extensively studied SRCs. Last generation experiments probe SRC by triple coincidence - A(e,e' np or pp)A-2 reaction - where both knock-out nucleons are detected at two fixed angles.

- The SRC pair is typically assumed to be at rest prior to the scattering and the kinematics reconstruction utilizes pre-defined 4-momentum transfer components determined from the fixed beam energy and the electron scattering angle and energy.

- The NN-SRCs are associated with finding a pair of high-momentum nucleons, whose reconstructed initial momenta are back-to-back and exceed $k_F$, while the residual nucleus is assumed to be left in a highly excited state after the interaction.

In neutrino scattering experiments one main limitation comes from the intrinsic uncertainty on the 4-momentum transfer, due to the not fixed (broadly distributed in the beam spectrum) incident neutrino energy. An estimate can be inferred with satisfactory accuracy when all final state particles kinematics is precisely measured.
With an approach similar to the electron scattering triple coincidence analysis, we applied transfer momentum vector subtraction to the higher proton momentum in our sub-sample of the remaining events with both protons above Fermi momentum. Events consistent with pre-existing at rest SRCs would show $\vec{p}_{n1} \sim \vec{p}_{p2}$, i.e. back-to-back in the initial state.

Results in a paper in preparation, presently under internal review.
CONCLUDING REMARKS

NUCLEAR EFFECTS (IN HEAVY NUCLEAR TARGETS) ARE IMPORTANT AND FAR MORE COMPLEX AND OVERWHELMING THAN USUALLY ASSUMED

Accurate and extremely detailed MonteCarlo generators are needed for comparison with LAr data, in particular for nuclear effects understanding (FSI+Nucleon-Nucleon correlations)

Data from LAr extremely helpful and can provide important hints to tune MC generators and discriminate among models

QE or not QE, that is the question

Future larger mass and high statistics LAr-TPC detectors have the opportunity to clarify the issue [following the line pioneered with the (statistically limited) ArgoNeuT data sample]
BACKUP
THE LAR TPC CONCEPT

Charged particle tracks ionize argon atoms; Ionization charge drifts to **finely segmented charge collection planes** over ~1-few ms.

**ArgoNeuT event**

Wire pulses in time give the drift coordinate of the track

**induction plane + collection plane + time** = 3D image of event (w/ calorimetric info)
The ArgoNeuT Detector

“The ArgoNeuT Detector in the NuMI Low-Energy beam line at Fermilab” JINST 7 (2012) P10019

The TPC, about to enter the inner cryostat

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Volume</td>
<td>500 Liters</td>
</tr>
<tr>
<td>TPC Volume</td>
<td>170 Liters</td>
</tr>
<tr>
<td># Electronic Channels</td>
<td>480</td>
</tr>
<tr>
<td>Wire Pitch</td>
<td>4 mm</td>
</tr>
<tr>
<td>Electronics Style (Temperature)</td>
<td>JFET (293 K)</td>
</tr>
<tr>
<td>Max. Drift Length</td>
<td>47 cm</td>
</tr>
<tr>
<td>Light Collection</td>
<td>None</td>
</tr>
</tbody>
</table>

- Self contained system
- Recirculate argon through a copper-based filter
- Cryocooler used to recondense boil-off gas
Example of Low energy proton reconstruction

ArgoNeuT proton threshold: 21 MeV of Kinetic Energy

Short (2 wires) track with high ionization superimposed to the muon track

The short track behaves like proton

Length = 0.5 cm
KE = 22 ± 3 MeV

* Kinetic energy vs track length (data)
• NIST predictions
ArgoNeuT pion reconstruction threshold: 
~8 MeV Kinetic energy
PROTON KINEMATICS:
BACKWARD GOING PROTONS (B_p)

Backward going protons are detected and reconstructed in ArgoNeuT DATA

A zoomed-in view: ν interaction with one backward going p

A zoomed-in view: ν interaction with two backward going p

DETAILED STUDY OF B_p IN PROGRESS
BACK-TO-BACK PROTON PAIR

Angle between two protons $\gamma = 177^0$

anti-Neutrino interaction producing a back-to-back proton pair
Red (blue): positive (negative) charge tracks determined by MINOS.
Direct access to nuclear effects requires:

- low threshold for proton detection (below Fermi level)
- neutron detection capability (p conversion via CEX) short heavily ionizing track detached from the vertex
- sensitivity to low energy de-excitation γ’s (via Compton Sc.)
Reconstruction of proton from neutron conversion

Proton at the vertex:
trk_length=2.91 cm, KE=39.5 MeV

Few events with n→p in ArgoNeuT (small LAr volume)