Results for quasi-elastic anti-neutrino scattering on scintillator from the MINERvA experiment

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Big question

- Why is almost everything matter instead of anti-matter?

- Answer may be CP-violating processes

- Make particle/anti-particle and compare behavior
  - Quarks $\rightarrow$ B, K decays
  - Neutrinos $\rightarrow$ oscillations
Neutrino CP violation

Neutrinos oscillate between flavors!
Do neutrinos and anti-neutrinos behave the same?
Not necessarily!

Study

\[ \nu_\mu \rightarrow \nu_e \]

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

probability of finding each type of neutrino

Oscillations for
\[ \nu_\mu \ @ \ 1300 \ km \]
CP phase \( \delta = -\pi/2 \)

Flips for \( \delta = \pi/2 \)
Need to understand anti-neutrino interactions!

- What do interactions look like?
- What is the neutrino energy?
- This is especially important for anti-neutrinos as processes like

\[ \bar{\nu} + p \rightarrow \ell^+ + n \]

have hard-to-reconstruct final states
Quasi-elastic scattering on nucleons (CCQE)

\[ E_{\nu}^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos \theta_\mu)} \]

\[ Q_{QE}^2 = 2E_{\nu}^{QE}(E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2 \]

In principle 2-body scatter from a nucleon at rest allows full reconstruction of the kinematics from the muon alone.
MINERvA Experiment @ Fermilab

5.4 Ton Active Scintillator Fiducial Volume
MINERvA

Quasi-elastic scattering on CH (scintillator)
Muons tracked and momentum analyzed
Protons > 120 MeV can be detected
Neutrons ~50% of the time

Classic signature:
• Final state muon analyzed in MINOS
• No extra recoil energy!!

Around 14,000 anti-neutrino candidates in this sample
X10 more coming soon!
Electron-scattering experiments have found that, approximately 20% of the time, electrons scattered from correlated pairs of nucleons instead of single nucleons.

~90% of these pairs consist of a proton and a neutron.

2p2h process

Initial interaction is not CCQE
But the observed event looks like it

Initial interaction is CCQE but the observed event is not!
Two strategies:

QE-like: define a signal that is corresponds to what we see in the final state.

CCQE: correct your signal back to what the initial interaction was.
Two strategies:

QE-like ($0\pi$): define a signal that corresponds to what we see in the final state. More accurate, harder to interpret.

CCQE: correct your signal back to what the initial interaction was. Less accurate, easier to interpret.
Practical signal definitions

**Ideal CCQE**
- One charged muon
- One neutron
- No protons
- No pions
- Low recoil activity

**CCQE-Like = 0π**
- One charged muon
- May not see the neutron
- No protons > 120 MeV
- No pions
- Low recoil activity
- We allow any number of neutrons to include 2p2h contributions
Lots of data – 2D measurement

Anti-ν
QE-like
Can we model this?

- Default GENIE 2.8.4
  - (Relativistic Fermi Gas)
- Add in Random Phase Approximation (RPA) to account for screening at low $Q^2$
- Add $\sim20\%$ 2p2h effects guided by Jlab results w/o RPA
- Add RPA and tune 2p2h to our neutrino data to get $M_{\nu\text{vGENIE}}$
How MINERvA tunes the simulation

- Read lots of papers
- Listen to our eN→eN colleagues
- Look at the neutrino data where the process is
  - $\nu_\mu + n \rightarrow \mu^- + p$
- Look for the final state neutrons in
  - $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- All of these indicate both a need for screening (RPA) at low Q2 and 2p2h effects.
- MINERvA tunes the 2p2h model on neutrino data
**Multinucleon Effects**

- Look at CC double differential cross section in $q_0$ and $q_3$
  - $q_0$: calorimetric hadronic energy (would be $\omega$ if $n$ could be detected)
  - $q_3$: is the three momentum transfer
  $$q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$$

Motivated by electron scattering data on C.

Fitting a 2D Gaussian in true \((q_0, q_3)\) as a reweighting function to the 2p2h contribution to get the best agreement between data and MC.

The QE and RES interactions are unchanged.
Nuclear Effects at low Three Momentum Transfer (Antineutrino)

- Applying the extracted 2p2h weights from the neutrino sample to antineutrino

Before

![Graph showing data distribution before applying weights]

After

![Graph showing data distribution after applying weights]

Neutron detection update

- MINERvA has a new neutron detection algorithm in scintillator

- Excess in the MC in the first bin small energy deposition
Bottom line

- Take Relativistic Fermi Gas model with final state interactions (GENIE 2.8.4)
- Add in screening (RPA) and multiparticle (2p2h) effects
- Use neutrino data to tune the 2p2h model.
- Get MnVGENIE model which agrees with our inclusive anti-neutrino data.
Back to inclusives now that we understand our simulation:

1-D distributions for QE-like
Systematic uncertainty sources

- Statistical uncertainty
- Background models
- CCQE / 2p2h model
- Final-state interactions
  - pion absorption dominates
- Flux
  - beam focusing
  - tertiary hadron production
  - reweight to other experiments
- Muon reconstruction
  - muon energy scale dominates
  - tracking efficiency
  - muon angle and vertex position
- Recoil reconstruction
  - detector response to different particles - neutron dominates
Switch to **CCQE** to compare to other experiments

Bridge the gap!

MINERνA result includes an angle cut which lowers rate for $E<4$ GeV
Conclusions

- We have measured anti-neutrino quasi-elastic scattering on scintillator with uncertainties dominated by the 7-8% flux normalization uncertainty.
- Bridges the gap between MiniBooNE and NOMAD
- Able to differentiate nuclear models – we favor a 2p2h component
- More details in Cheryl Patrick’s June 17 seminar and her thesis (FNAL THESIS-2016-04)
- Published as 10.1103/PhysRevD.97.052002
- Data tables at: https://arxiv.org/abs/1801.01197
- Data from Medium Energy Run at higher energy coming soon.
The anti-neutrino team:
Heidi Schellman, Cheryl Patrick, Laura Fields
Backup slides
**NuMI low energy anti-neutrino flux**

![Graph showing the MINERνA antineutrino flux with constrained and unconstrained data.]
Muon kinematics acceptance

We measure the cross section in \(~60\) muon $p_Z, p_T$ bins

2-D cross sections are normalized to integrated neutrino flux per nucleon
Model details

- We use GENIE 2.8.4 as our baseline Monte Carlo generator

- **Nuclear effects**
  - Relativistic Fermi Gas model with Bodek-Ritchie tail
  - Fermi momentum $k_F = 221$ MeV
  - non-resonant pion production scaled by 57% to match fits to bubble chamber data as detailed in arXiv:1601.01888
  - RPA and 2p2h are added for the MnvGENIE model we use to correct our data.

- **Nucleon effects**
  - Proton form factor Axial mass $M_A = 0.99$ GeV
  - BBBA05 model for vector form factors
Cross section vs $Q^2$

$\frac{d\sigma}{dQ_{QE}^2}$ (cm$^2$/GeV$^2$/nucleon)

$1.5 < E_{\nu}^{QE} < 2$ GeV

$2 < E_{\nu}^{QE} < 2.5$ GeV

$2.5 < E_{\nu}^{QE} < 3$ GeV

$3 < E_{\nu}^{QE} < 3.5$ GeV

$3.5 < E_{\nu}^{QE} < 4$ GeV

$4 < E_{\nu}^{QE} < 5$ GeV

$5 < E_{\nu}^{QE} < 6$ GeV

$6 < E_{\nu}^{QE} < 7$ GeV

$7 < E_{\nu}^{QE} < 8$ GeV

$8 < E_{\nu}^{QE} < 10$ GeV

$Q_{QE}^2$ (GeV$^2$)
Model references

- GENIE: C. Andreopoulos et al., arXiv:1510.05494
Anti-Neutrino Flux

Energy (GeV)

Anti-Neutrinos/cm²/GeV/POT

Medium Energy

Low Energy

Today’s data

MINERvA Preliminary