Update on JLab Experiment E12-14-012:

Inclusive \((e,e')\) and Exclusive \((e,e'p)\) Electron Scattering from \(^{12}\text{C}, ^{48}\text{Ti}\) and \(^{40}\text{Ar}\).

Daniel L. Abrams

UNIVERSITY of VIRGINIA

Hall A Collaboration Meeting
January 30, 2019
Presentation Outline

Experiment E12-14-012

• Motivation - Neutrino oscillations
• Physics - electron scattering from nuclei
• HRS kinematics
• Argon target cell

Part I: Inclusive Analysis

• Cross Section Extraction Methods
• Systematic Uncertainties
• Results

Part II: Exclusive Analysis

• Particle Identification
• Preliminary Analysis Results
JLab Experiment E12-14-012:

**Primary Goal:** Measurement of the spectral functions of argon through coincidence \((e,e'p)\) scattering off of \(^{40}\text{Ar}\) and \(^{48}\text{Ti}\).

**Primary Motivation:** To help improve the accuracy of the measurement of the neutrino oscillation parameters (including the CP violation in the leptonic sector) in future neutrino experiments, such as LBNE/DUNE.

The argon spectral function is key to the reconstruction of neutrino energies, currently the largest source of uncertainty in neutrino experiments.

Virtually no argon-electron scattering data available - collection of coincidence \((e,e'p)\) data will serve as a benchmark to test nuclear models against.
Electron Scattering from Nuclei

Exclusive (e,e′p): Scattered electron and knocked-out proton detected in coincidence

\[
\frac{d^6 \sigma_A}{dE_e' d\Omega_e' dE_p d\Omega_p} = K \frac{\alpha^2}{Q^4} \frac{E_{e'}}{E_e} L^{\mu\nu} W_{\mu\nu}
\]

\(L^{\mu\nu}\) is the leptonic tensor

\(W_{\mu\nu}\) is the target response tensor

\(K\) a kinematical factor

Single particle wave functions \(\Phi_i(p)\) with energies \(\epsilon_i\) are the basic quantities accessed in knockout reactions

Can construct a probability function to describe the shell structure of the nucleus:

\[
S(|p|, E) = \sum_i |\Phi_i(p)|^2 \delta(E + \epsilon_i)
\]

\[
d^6 \sigma \propto S(|p|, E)
\]

Inclusive (e,e′): Only scattered electron detected

Integrate over exclusive spectrum to get inclusive cross section:

\[
\frac{d^2 \sigma}{d\Omega dE'} \propto \int d^3 p \int dE'_p \left( \frac{d\sigma_p}{d\Omega_e} \right) S(|p|, E'_p) \delta(\ldots)
\]

Energy integral of spectral function gives nucleon momentum distribution:

\[
n(p) \propto \int dE'_p S(p, E'_p)
\]
Exploiting the correspondence of the level structures of $^{40}\text{Ar}$ and $^{48}\text{Ti}$, the neutron spectral function can be obtained from the proton spectral function of titanium.

$^{40}\text{Ar} (e,e'p)$ gives the proton spectral function for Ar

$e + ^{18}_{40}\text{Ar} \rightarrow e' + p + X \quad \Longrightarrow \quad S_p(|\vec{p}|, E)$

$^{48}\text{Ti} (e,e'p)$ gives the neutron spectral function for Ar

$e + ^{22}_{48}\text{Ti} \rightarrow e' + p + X \quad \Longrightarrow \quad S_n(|\vec{p}|, E)$
Electron Scattering from Nuclei

Plane Wave Impulse Approximation (PWIA)

- Scattering off of nuclear target reduces to incoherent sum of elementary scattering processes involving individual bound nucleons
- FSI between proton and recoiling nucleus are negligible

\[ \sigma = K \left( \frac{d\sigma_p}{d\Omega_e} \right) S(|\vec{p}_m|, E_m) \]

Distorted Wave Impulse Approximation (DWIA)

- Accounts for FSI with spin-independent optical potential
- Appropriate choice of kinematics reduces FSI
- Potential has minimal effect on outgoing proton momentum
- Factorization of differential cross-section holds!
- DWIA implemented in MC using Carlotta’s code

\[ \frac{d^6\sigma_A}{dE_{e'}d\Omega_{e'}dE_{p}d\Omega_{p}} = K \left( \frac{d\sigma_p}{d\Omega_e} \right) S^{D}(E_m, |\vec{p}_m|, |\vec{p}|) \]

\( K \) a kinematic factor
\( \frac{d\sigma_p}{d\Omega_e} \) the elastic electron-proton cross section
\( S(|\vec{p}_m|, E_m) \) the spectral function

16O Spectral Function
Connection to Neutrino Physics

How does the Argon spectral function help with neutrino physics?

The reconstruction of (anti-)neutrino energy in the LArTPC detectors requires understanding of the spectral functions describing both neutrons and protons.

\[
E_\nu = \frac{m_n^2 - m_\mu^2 - E_p^2 + 2E_\mu E_p - 2|k_\mu||P_p| + P_p^2}{2(E_p - E_\mu + |k_\mu| \cos \theta_\mu - |P_p| \cos \theta_p)}
\]

\( E_p \) and \( P_p \) are distributed according to the proton spectral function.

In the detectors, the neutrinos will interact with the argon nucleus through the charged-current weak interactions: \( \nu_l + n \rightarrow l^- + p \) and \( \bar{\nu}_l + p \rightarrow l^+ + n \)

Physics of these neutrino interactions is analogous to \( (e,e'p) \)

In the PWIA/DWIA approximation scheme, the neutrino cross sections can be written in terms of a spectral function.

The spectral function is an intrinsic property of the nuclear ground state, and hence can describe interactions involving different particle probes.
Data collection from Feb-March 2017

Ar/Ti/C(\(e,e'p\)) for five kinematic settings

Ar/Ti/C(\(e,e'\)) for kin5 only

Data collection used “parallel kinematics” to reduce the effects of FSI on the cross-section

\[
\begin{array}{ccccccccc}
E_e & E_{e'} & \theta_e & P_p & \theta_p & |q| & p_m & x \\
\text{MeV} & \text{MeV} & \text{deg} & \text{MeV/c} & \text{deg} & \text{MeV/c} & \text{MeV/c} \\\n\hline
\text{kin1} & 2222 & 1799 & 21.5 & 915 & -50.0 & 857.5 & 57.7 & 0.70 \\
\text{kin2} & 2222 & 1716 & 20.0 & 1030 & -44.0 & 846.1 & 183.9 & 0.48 \\
\text{kin3} & 2222 & 1799 & 17.5 & 915 & -47.0 & 740.9 & 174.1 & 0.47 \\
\text{kin4} & 2222 & 1799 & 15.5 & 915 & -44.5 & 658.5 & 229.7 & 0.37 \\
\text{kin5} & 2222 & 1716 & 15.5 & 1030 & -39.0 & 730.3 & 299.7 & 0.29 \\
\end{array}
\]
E12-14-012 Targets

- Carbon
- Titanium
- Argon
- 25cm Al dummy
- Optics

C and Ti targets are foils
Ar target is a sealed gas cell

Length = 25 cm
Pressure = 500 PSI
Temperature = 300 K

Dummy target: same as the entry and exit window as the gas target

Optical target: a series of foils of carbon (9) to check the alignment of target and spectrometers (optics)
E12-14-012 Argon Target Boiling Study

Calculate normalized yield for different currents

A change in the yield represents a change in the target density: \( \Delta Y \Rightarrow \Delta \rho_{\text{targ}} \)

Fit the yield data with a function \( f(I_{\text{CEBAF}}) \) such that \( f(0) = 1 \)

Density correction factor:

\[
f(I_{\text{CEBAF}}) = a \cdot I_{\text{CEBAF}}^2 + b \cdot I_{\text{CEBAF}} + c
\]

Boiling study courtesy of Nathaly Santiesteban.
Available at: arXiv:1811.12167
PART I

Inclusive \((e,e')\) Scattering from \(^{12}\text{C}\), \(^{48}\text{Ti}\), \(^{40}\text{Ar}\), and \(^{27}\text{Al}\)
Cross Section Extraction Methods

**Acceptance Method:**

Number of detected events:

\[ N^− - BG = L \cdot \sigma \cdot (\Delta E' \Delta\Omega) \cdot \varepsilon \cdot A(E',\theta) \]

Let \( Y = N^− - BG \), and solve for the cross-section:

\[
\left( \frac{d^2\sigma}{d\Omega dE'} \right)_{exp} = \frac{Yield}{L \cdot \varepsilon \cdot (\Delta E' \Delta\Omega) \cdot A(E',\theta)}
\]

**Yield Ratio Method:**

Calculate the “yield” for both the data and MC simulation:

\[
Yield = \frac{N_s \cdot DAQ_{pre-scale}}{N_e \cdot LT \cdot \varepsilon}
\]

Multiply model cross section by data/MC yield ratio:

\[
\left( \frac{d^2\sigma}{d\Omega dE'} \right)_{exp} = \left( \frac{d^2\sigma}{d\Omega dE'} \right)_{MC} \cdot \frac{Yield_{data}}{Yield_{MC}}
\]

**Carbon Comparison Method:**

Scale the Carbon cross section by the titanium-to-carbon yield ratio:

\[
\left( \frac{d^2\sigma}{d\Omega dE'} \right)^i_{Ti} = \left( \frac{d^2\sigma}{d\Omega dE'} \right)^i_C \cdot \frac{Yield^i_{Ti}}{Yield^i_C}
\]
Inclusive Analysis: Systematic Uncertainty

Total systematic uncertainty ≈ 3%

- Beam charge ~ 0.3 %
- Beam energy ~ 0.1 %
- Beam x and y offset ~ 0.8 %
- HRS x and y offset ~ 0.8 %
- Target boiling ~ 0.7 %
- Acceptance ~ 0.6 %
- Cherenkov cut ~ 0.02 %
- COSY ~ 0.64 %
- Radiative corrections ~ 1 %
  - RC on model ~ 0.49 %

Radiative corrections calculated using the peaking approximation of Mo and Tsai.

To determine the effect of the cross section model used to calculate the radiative correction factor, we scaled the original MC model by $\sqrt{Q^2/2}$ and recalculated the correction factor.

$$RC = \frac{\sigma_{\text{born}}}{\sigma_{\text{rad}}}$$

We use the code COSY to generate the optical matrix for simulation.

To estimate the optical matrix uncertainty due to the magnetic field settings of Q1, Q2, and Q3, we varied the individual settings by 1%
$^{12}\text{C}(e,e')$ Cross Section

$\sigma_{\text{stat}} < 1.20\%$

$\sigma_{\text{syst}} < 2.95\%$

Compare result with MC model:

Results published in Phys. Rev. C 98, 014617
$^{48}\text{Ti}(e,e')$ Cross Section

$E_0 = 2.222 \text{ GeV}$

$\theta = 15.541^\circ$

$\sigma_{\text{stat}} < 1.24\%$

$\sigma_{\text{syst}} < 2.63\%$

Compare result with MC model:

Results published in Phys. Rev. C 98, 014617
\textbf{\textsuperscript{40}Ar(e,e')} Cross Section

\[ \sigma_{\text{stat}} \leq 2.9\% \]

\[ \sigma_{\text{syst}} \leq 3.0\% \]

Compare result with MC model:

Available at: arXiv:1810.10575, under review at PRL
$^{27}\text{Al}(e,e')$ Cross Section

$E_0 = 2.222 \text{ GeV}$

$\theta = 15.541^\circ$

$\sigma_{syst} \leq 2.7\%$

Compare yield and acceptance methods:
Inclusive Cross Sections Per Nucleon

\[ \frac{\text{nb/str}}{\text{GeV/A}} \]

\[ \begin{align*}
12\text{C}(e, e') \\
48\text{Ti}(e, e') \\
40\text{Ar}(e, e')
\end{align*} \]
PART II

Exclusive \((e,e'p)\) Scattering from \(^{40}\text{Ar}\): Preliminary Analysis
E12-14-012 Exclusive Analysis

**LHRS Data Cuts**

- $dp$: (0.01, 0.04)
- $\theta$: $(-0.04, 0.04)$
- $\phi$: $(-0.02, 0.015)$
- Vertex Z: ± 9 cm

**RHRS Data Cuts**

- $dp$: (0, 0.03)
- $\theta$: $(-0.04, 0.04)$
- $\phi$: $(-0.02, 0.015)$
- $\beta > 0.6$

Coincidence Time: ±1σ
(e,e'p) Particle Identification and Proton Selection

Coincidence trigger cut: T1

Coincidence time: \( L.s0.time - R.s0.time \)

Coincidence Time: L.s0.time - R.s0.time

\[
\begin{array}{|c|}
\hline
\text{hcoinc} \\
\text{Entries} & 10631 \\
\text{Mean} & -2.995 \times 10^{-6} \\
\text{RMS} & 3.371 \times 10^{-8} \\
\hline
\end{array}
\]

\[ \pm 3\sigma \sim 3 \pm 0.6\% \]

\[ \pm 1\sigma \sim 0.8 \pm 0.04\% \]

\[ e + p \rightarrow e' + p + \pi^0 \quad \text{True coincidence!} \]

\[ e + p \rightarrow e' + n + \pi^+ \]

\[ e + n \rightarrow e' + p + \pi^- \quad \text{Accidental coincidences!} \]

RHRS \( \beta: R.tr.beta \)

\[
\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}
\]

RHRS \( \Delta\beta = \beta - P/E, \text{Proton, Run 370, kin1} \)
E12-14-012 Exclusive Analysis

Analysis of full exclusive data underway for Ar target, Ti analysis upcoming

Using MCEEP for MC model

MCEEP Input file:
\( e^- \) Arm \( P_0 \): 1762 GeV
\( e^- \) Arm Spec. \( \theta \) offset: -7 mrad
\( p \) Arm Spec. \( \theta \) offset: -7 mrad

Data: Run 370
\( e^- \) Arm \( P_0 \): 1777 GeV

Red: normalized data
Blue: MCEEP
E12-14-012 Exclusive Analysis

**Lphi_data**
- Entries: 85450
- Mean: 0.003444
- RMS: 0.01011

**Rphi_data**
- Entries: 85450
- Mean: 0.002226
- RMS: 0.009537

**Z_data**
- Entries: 85450
- Mean: 0.0004776
- RMS: 0.04832

**beta_data**
- Entries: 85450
- Mean: 0.6943
- RMS: 0.04345
E12-14-012 Exclusive Analysis

**Em_data**
- Entries: 85450
- Mean: 0.02172
- RMS: 0.01083

**Em_data**

**Pm_data**
- Entries: 85450
- Mean: 0.09857
- RMS: 0.01938

**Pm_data**

**Pm1_data**
- Entries: 30682
- Mean: 0.1016
- RMS: 0.01803

**Pm1_data**

**Pm2_data**
- Entries: 29140
- Mean: 0.09476
- RMS: 0.01893

**Pm2_data**
Whats next for exclusive analysis?

Include FSI in calculations

Isolate shells with cut on $E_{\text{miss}}$

Calculate momentum distribution $n(p)$ for each shell

Repeat everything for titanium!
Special Thanks To:

Donal Day†, Dien Nguyen
*Department of Physics, University of Virginia*

Hongxia Dai, Matt Murphy, Vishvas Pandey, Camillo Mariani†
*Center for Neutrino Physics, Virginia Tech*

Douglas Higinbotham†
*Jefferson Lab, Hall A E12-014-012 Collaboration*

Omar Benhar
*Dipartimento di Fisica, “Sapienza” Università di Roma*

Nathaly Santiesteban
*Department of Physics and Astronomy, University of New Hampshire*

MCEEP by P. Ulmer

†E-12-14-012 spokesperson