Neutrino interactions and the quest for new and precision physics searches in neutrino experiments

Vishvas Pandey
Neutrinos: the portal to new frontiers in physics

Neutrino interactions: a multi-scale, multi-process problem

Tackling neutrino interactions
Neutrinos: the portal to new frontiers in physics

Neutrino interactions: a multi-scale, multi-process problem

Tackling neutrino interactions
Standard Model
- Need to explore physics Beyond the Standard Model (BSM)
Beyond the Standard Model and Neutrinos

**Standard Model**

- **Flavor States**
  - $\nu_e$
  - $\nu_\mu$
  - $\nu_\tau$
- **Mass States**
  - $\nu_1$
  - $\nu_2$
  - $\nu_3$

**Mixing Matrix**

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

**Neutrino Oscillation**

For the discovery of neutrino oscillations which shows neutrino has mass.
Beyond the Standard Model and Neutrinos

### Standard Model

- **1st** generation: electron, muon, tau
- **2nd** generation: charm, bottom, top
- **3rd** generation: down, strange

### Neutrino Oscillation

**Oscillation Probability:**

\[
P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right)
\]

- The mixing angle, \(\theta\), sets the amplitude of the oscillation
- \(\Delta m^2\) determines the frequency of the oscillation
- \(L = \) distance traveled, \(E = \) neutrino energy

**Mixing Matrix**

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

**Flavor States**

**Mass States**

For the discovery of neutrino oscillations which shows neutrino has mass.
These are exciting times. We are at the beginning of a new era in our understanding of the Universe and a new era of discoveries!

**Building Neutrino Experiments**

- Measure neutrino properties:

- Use neutrinos as a probe for BSM physics:

- Enabling multi-messenger astronomy:
The Brave $\nu$ World

These are exciting times. We are at the beginning of a new era in our understanding of the Universe and a new era of discoveries!

✿ **Building Neutrino Experiments**

- Measure neutrino properties:
  - Determine neutrino masses and hierarchy
  - Determine neutrino mixing parameters
  - Determine CP violation phase

- Use neutrinos as a probe for BSM physics:

- Enabling multi-messenger astronomy:

---

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Normal Hierarchy (NH) vs. Inverted Hierarchy (IH)

- $m^2$ vs. $m^2$
- $\Delta m^2_{atm}$
- $\Delta m^2_{sol}$
- $\nu_e$, $\nu_\mu$, $\nu_\tau$

---

Matter-Antimatter Asymmetry

Credit: Symmetry Magazine / Sandbox Studio, Chicago
These are exciting times. We are at the beginning of a new era in our understanding of the Universe and a new era of discoveries!

**Building Neutrino Experiments**

- Measure neutrino properties:
  - Determine neutrino masses and hierarchy
  - Determine neutrino mixing parameters
  - Determine CP violation phase

- Use neutrinos as a probe for BSM physics:
  - Additional neutrino flavors (*sterile neutrinos*)
  - Dark matter
  - …..

- Enabling multi-messenger astronomy:
  - Detecting Supernova
  - …..

---

**Fermion Masses**

- $\nu_1$ (electron neutrino)
- $\nu_2$ (muon neutrino)
- $\nu_3$ (tau neutrino)

**Normal Hierarchy (NH)**

- $m^2$ (squared mass difference)
- $\Delta m^2_{atm}$ (atmospheric neutrino oscillation)
- $\Delta m^2_{sol}$ (solar neutrino oscillation)

**Inverted Hierarchy (IH)**

- $m^2$ (squared mass difference)
- $\Delta m^2_{sol}$ (solar neutrino oscillation)
- $\Delta m^2_{atm}$ (atmospheric neutrino oscillation)

---

**Matter-Antimatter Asymmetry**

Credit: Symmetry Magazine / Sandbox Studio, Chicago
Neutrinos Sources and Experiments of My Interest

\[ \nu_\mu \rightarrow \mu^+ \nu_\mu \,(99.98\%) \]

\[ p \rightarrow \pi^0, K^+, \pi^+ \rightarrow \eta, \pi^- \]

Target

Magnetic Focusing Horn

10 MeV, 100 MeV, 1 GeV, 10 GeV

U. Mosel
Neutrinos Sources and Experiments of My Interest

\[ K^+ \rightarrow \mu^+ \nu_\mu (63.4\%) \]

Kaon decay at rest

\[ p \rightarrow \text{Target} \]

Magnetic Focusing Horn

Energy Distribution

- BNB \( \nu \)
- LBNF \( \nu \)
- MINER\(\text{A} \) \( \nu \)
- T2K ND \( \nu \)
- NOvA ND \( \nu \)

U. Mosel

J. Spitz

236 MeV

10 MeV - 100 MeV - 1 GeV - 10 GeV

\( 10 \text{ MeV} \)
\( 100 \text{ MeV} \)
\( 1 \text{ GeV} \)
\( 10 \text{ GeV} \)
Neutrinos Sources and Experiments of My Interest

- Magnetic Focusing Horn
- Target
- Pion decay at rest and Supernova

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

10 MeV  100 MeV  1 GeV  10 GeV

J. Spitz

π^+ → μ^+ ν_μ
μ^+ → e^+ ν_e ̅ν_μ

K. Scholberg

Pion decay at rest and Supernova

U. Mosel

π\(^0\) → K^+ K^-
K^+ → π^+ π^-
η → π^+ π^- π^0

Flux (neutrinos per 0.2 MeV per cm\(^2\))
Liquid Argon Detectors
Neutrinos Sources and Experiments of My Interest

Short-Baseline Neutrino (SBN) Program at FNAL

Deep Underground Neutrino Experiment (DUNE) at FNAL

Coherent CAPTAIN-Mills (CCM) Experiment at LANL

Low-Energy Physics in DUNE

Liquid Argon Detectors
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Tackling neutrino interactions
Neutrino Oscillation Experiment

DUNE

Sanford Underground Research Facility

800 miles

Underground Particle Detector

Particle Detector

Neutrino Production

Existing Proton Accelerator

Existing Labs

Fermilab

http://lbnf.fnal.gov/
Event Rate at Near Detector:

\[ N_{ND}^\alpha (E_{\nu, \text{rec}}) \propto \sum_i \phi_\alpha (E_{\nu}) \times \sigma_i^\alpha (E_{\nu}) \times \epsilon_\alpha (E_{\nu}, E_{\nu, \text{rec}}) \]
Oscillation Probability:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E_\nu} \right) \]

Event Rate at Near Detector:

\[ N_{ND}^\alpha (E_{\nu,rec}) \propto \sum_i \phi_\alpha (E_\nu) \times \sigma_i^\alpha (E_\nu) \times c_\alpha (E_\nu, E_{\nu,rec}) \]
DUNE

Neutrino Oscillation Experiment

**Event Rate at Far Detector:**

\[ N_{FD}^{\alpha \rightarrow \beta}(E_{\nu,\text{rec}}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_i^\beta(E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta) \times \epsilon_\beta(E_\nu, E_{\nu,\text{rec}}) \]

**Event Rate at Near Detector:**

\[ N_{ND}^{\alpha}(E_{\nu,\text{rec}}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_i^\alpha(E_\nu) \times \epsilon_\alpha(E_\nu, E_{\nu,\text{rec}}) \]

**Oscillation Probability:**

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \times \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4 E_\nu} \right) \]

DUNE
Neutrino Energy and Neutrino-nucleus Interactions

\[
N_{FD}^{\alpha \rightarrow \beta}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_{\nu}) \times \sigma_\beta^i(E_{\nu}) \times P(\nu_\alpha \rightarrow \nu_\beta \times E_{\nu}, E_{\nu,rec})
\]

\[
N_{ND}^{\alpha}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_{\nu}) \times \sigma_\alpha^i(E_{\nu}) \times \epsilon_{\alpha}(E_{\nu}, E_{\nu,rec})
\]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4 E_{\nu}} \right)
\]
**Neutrino Energy and Neutrino-nucleus Interactions**

\[
N_{FD}^\alpha \rightarrow _\beta (E_{\nu,\text{rec}}) \propto \sum_i \phi_\alpha (E_{\nu}) \times \sigma_\beta^i (E_{\nu}) \times P(\nu_\alpha \rightarrow \nu_\beta) \times \epsilon_\beta (E_{\nu}, E_{\nu,\text{rec}})
\]

\[
N_{ND}^\alpha (E_{\nu,\text{rec}}) \propto \sum_i \phi_\alpha (E_{\nu}) \times \sigma_\alpha^i (E_{\nu}) \times \epsilon_\alpha (E_{\nu}, E_{\nu,\text{rec}})
\]

**Neutrino Energy:**

Energy Reconstruction:

\[
E_{\nu} = \sum E_{\text{observed particles}} + E_{\text{neutrons}} + E_{\text{missing}}
\]

Neutrino energy reconstruction requires predictions from the interaction model.
Neutrino Energy and Neutrino-nucleus Interactions

Neutrino-nucleus Interactions:

- Neutrino fluxes span over a wide range of energies where a number of complex nuclear reaction mechanisms overlap.
Neutrino fluxes span over a wide range of energies where a number of complex nuclear reaction mechanisms overlap.
**Neutrino Energy and Neutrino-nucleus Interactions**

- **Nucleus as a many-body system with pions and nucleons as (effective) d.o.f.**
- **Multi-scale, multi-process, many-body, non-perturbative problem subject to complex nuclear structure and dynamics.**
- **Transition from the hadronic d.o.f. to quark d.o.f**

**Atomic Systems**

- QCD
  - d.o.f.: quarks and gluons
  - Asymptotic freedom
  - Confinement
No unified theory, different models predict different cross sections.

Steven Gardiner


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Tackling neutrino interactions
Tackling Neutrino Interactions

Lepton-nucleus Scattering Theory

Neutrino Experiments

Electron Scattering Experiments
Electron Scattering Experiments

- Electron beams have well known energy. Kinematics of interests can be separated.

- The vector current is conserved between electromagnetic and weak interactions.

- The ground state nuclear properties and nuclear effects (final state interactions, etc.) are same.
Neutrino Experiments

- Not possible to separate different processes
- Axial contributions
- $\nu_\mu$ to $\nu_e$ differences: lepton mass effects, electron or muon in the final state experience different coulomb effects
- $\nu$ to $\bar{\nu}$ differences: for isospin asymmetric nuclei, $^{40}\text{Ar}$, neutrinos and antineutrinos may behold different nuclear effects

- Lepton-nucleus Scattering Theory
  - Microscopic consistent model
  - Tested and developed against electron and neutrino data
  - Implemented in neutrino generators
Tackling Neutrino Interactions

Lepton-nucleus Scattering Theory

Electron Scattering Experiments

Neutrino Experiments

Precision Oscillation and BSM Physics

*Discoveries*
Measuring \((e, e')\) and \((e, e'p)\) cross sections on Ar, Ti (and C, Al) nuclei.

Measuring spectral functions of Ar nucleus.

**Electron-argon Experiment at JLab Hall A [E12-14-012]**

**Scientific Rating:** A

**Recommendation:** Approve

**Title:** Measurement of the Spectral Function of \(^{40}\text{Ar}\) through the \((e,e'p)\) reaction

**Spokespersons:** O. Benhar, C. Marini, C.-M. Jen, D.B. Day, D. Higinbotham

**Motivation:** This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on the spectral functions of neutrons and protons in \(^{40}\text{Ar}\). The neutrino beam has an energy spread and hence the neutrino flux as a function of energy has to be extracted by simulations that include the correct nuclear physics. A challenge is that the next generation of neutrino oscillation experiments aim at a precision of 1\% and hence ensuring that the nuclear corrections are properly addressed is critical. This data will provide experimental input to construct the argon spectral function, thus allowing the most reliable estimate of the neutrino cross sections. In addition, the analysis of the \((e,e'p)\) data will help a number of theoretical developments, such as the description of final-state interactions needed to isolate the initial-state contributions to the observed single-particle peaks, that is also needed for the interpretation of the signal detected in neutrino experiments.
- Measuring \((e, e')\) and \((e, e'p)\) cross sections on Ar, Ti (and C, Al) nuclei.

- Measuring spectral functions of Ar nucleus.

**Spectral Function**

- The spectral function, \(P(k,E)\), yields the probability of removing a nucleon of momentum \(k\) from the nuclear ground state leaving the residual system with excitation energy \(E\).
We study the coincidence \((e, e'p)\) processes in the kinematical region in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

**Coincidence \((e,e'p)\) process:**

- Both the outgoing electron and the proton are detected in coincidence, and the recoiling nucleus can be left in any bound state.

- Within the Plane Wave Impulse Approximation (PWIA) scheme:

\[
\frac{d\sigma_A}{dE_e' d\Omega_e' dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)
\]

- The initial energy and momentum of the knocked out nucleon can be identified with the measured missing momentum and energy, respectively as

\[
\begin{align*}
p_m &= p - q \\
E_m &= \omega - T_p - T_{A-1} \sim \omega - T_p
\end{align*}
\]

Where \(T_p = E_p - m\), is the kinetic energy of the outgoing proton.
HALL A Schematics

High Resolution Spectrometer

Superconducting magnets:
- large acceptance in both angle and momentum
- good resolution in position and angle

Detector Package:

Vertical Drift Chambers:
- collecting tracking information (position and direction)

Scintillators:
- trigger to activate the data-acquisition electronics
- precise timing information for time-of-flight measurements and coincidence determination

Cherenkov:
- The particle identification, obtained from a variety of Cherenkov type detectors (aerogel and gas) and lead-glass shower counters
Electron-argon Experiment at JLab Hall A [E12-14-012]

**Kinematic Setups**

| $E_e$ | $E_{e'}$ | $\theta_e$ | $P_p$ | $\theta_p$ | $|q|$ | $p_m$ |
|-------|--------|-------|-------|-------|-------|-------|
| MeV   | MeV    | deg   | MeV/c | deg   | MeV/c | MeV/c |
| kin1  | 2222   | 1799  | 21.5  | 915   | -50.0 | 857.5 | 57.7  |
| kin3  | 2222   | 1799  | 17.5  | 915   | -47.0 | 740.9 | 174.1 |
| kin4  | 2222   | 1799  | 15.5  | 915   | -44.5 | 658.5 | 229.7 |
| kin5  | 2222   | 1716  | 15.5  | 1030  | -39.0 | 730.3 | 299.7 |
| kin2  | 2222   | 1716  | 20.0  | 1030  | -44.0 | 846.1 | 183.9 |
| Inc-kin5 | 2222 | -     | 15.5  |       |       | 730.3 | 299.7 |

**Run Period: Feb-Mar 2017**

**kin1**

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First high-precision electron-argon cross section measurement, vital input to liquid argon based neutrino program.
Lepton-nucleus Scattering: HF-CRPA Model

- A microscopic many–body nuclear theory model. Nuclear ground state is described as a many-body quantum mechanical system where nucleons are bound in an effective nuclear potential.

- Solve Hartree-Fock (HF) equation with a Skyrme (SkE2) nuclear potential to obtain single–nucleon wave functions for the bound nucleons in the nuclear ground state.

- Introduce long-range correlations between the nucleons through the continuum Random Phase Approximation (CRPA).
Lepton-nucleus Scattering: HF-CRPA Model

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- Solve Hartree-Fock (HF) equation with a Skyrme (SkE2) nuclear potential to obtain single–nucleon wave functions for the bound nucleons in the nuclear ground state.

- Introduce long-range correlations between the nucleons through the continuum Random Phase Approximation (CRPA).

\[
\Pi^{(RPA)}(x_1, x_2; \omega) = \Pi^{(0)}(x_1, x_2; \omega) + \frac{1}{\hbar} \int dx \int dx' \Pi^{(0)}(x_1, x; \omega) \tilde{V}(x, x') \Pi^{(RPA)}(x', x_2; \omega)
\]

- Naturally includes: Binding, Fermi motion, elastic final state interaction (distortion of the outgoing nucleon in real MF potential), Pauli blocking, and orthogonality (both bound and scattered nucleon wave-functions are computed in the same nuclear potential).
A consistent many-body theory framework that describes lepton-nucleus processes from threshold to QE region: CEvNS, low-energy inelastic (supernova neutrinos) and QE processes.
Lepton-nucleus Scattering Cross Section

\[ \sum_{f_i} |\mathcal{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu} \]

- **Leptonic Tensor:**
  \[ L_{\mu\nu} = \sum_{f_i} (\mathcal{J}_{l,\mu})^\dagger \mathcal{J}_{l,\nu} \]

- **Hadronic Tensor:**
  \[ W^{\mu\nu} = \sum_{f_i} (\mathcal{J}_{n}^{\mu})^\dagger \mathcal{J}_{n}^{\nu} \]

- **Transition Amplitude:**
  \[ \mathcal{J}_{n}^{\mu} = \langle \Phi_f | \hat{J}_n^{\mu}(q) | \Phi_0 \rangle \]

\[ \omega = E_i - E_f, \quad q = |\vec{k}_i - \vec{k}_f|, \quad Q^2 = q^2 - \omega^2 \]
\[
\sum_{f_i} |\mathcal{M}|^2 \propto \frac{G_F^2}{2} L_{\mu \nu} W^{\mu \nu}
\]

- **Leptonic Tensor:** \( L_{\mu \nu} = \sum_{f_i} (\mathcal{J}_{l,\mu})^\dagger \mathcal{J}_{l,\nu} \)
- **Hadronic Tensor:** \( W^{\mu \nu} = \sum_{f_i} (\mathcal{J}_{n,\mu}^\dagger \mathcal{J}_{n,\nu} \)
- **Transition Amplitude:** \( \mathcal{J}_{n,\mu}^\dagger = \langle \Phi_f | \hat{J}_{n,\mu}(q) | \Phi_0 \rangle \)

- **Electron-nucleus cross sections:**
  \[
  \left( \frac{d^2 \sigma}{d\omega_e d\Omega} \right)_e = \frac{\alpha^2}{Q^4} \left( \frac{2}{2J_i + 1} \right) \frac{1}{k_f E_i} \times \zeta^2 (Z', E_f, q_e) \left[ \sum_{J=0}^{\infty} \sigma_{L,e}^J + \sum_{J=1}^{\infty} \sigma_{T,e}^J \right]
  \]
  \[
  \sigma_{L,e} = v_e^L R_e^L
  \]
  \[
  \sigma_{T,e} = v_e^T R_e^T
  \]
  - \( \zeta^2 (Z', E_f, q_e) \) takes care of the influence of the Coulomb field of nucleus on the outgoing charged lepton.

- **Neutrino-nucleus cross sections:**
  \[
  \left( \frac{d^2 \sigma}{d\omega_\nu d\Omega} \right)_\nu = \frac{G_F^2 \cos^2 \theta_c}{(4\pi)^2} \left( \frac{2}{2J_i + 1} \right) \varepsilon_f \kappa_f \times \zeta^2 (Z', \varepsilon_f, q_\nu) \left[ \sum_{J=0}^{\infty} \sigma_{CL,\nu}^J + \sum_{J=1}^{\infty} \sigma_{T,\nu}^J \right]
  \]
  \[
  \sigma_{CL,\nu}^J = \left[ v_\nu^M R_\nu^M + v_\nu^L R_\nu^L + 2 v_\nu^{MC} R_\nu^{MC} \right]
  \]
  \[
  \sigma_{T,\nu}^J = \left[ v_\nu^T R_\nu^T \pm 2 v_\nu^{TT} R_\nu^{TT} \right]
  \]
  - \( \sigma_L \) and \( \sigma_T \) are summed over multipoles corresponds to discrete and continuum states of a nucleus having angular momentum and parity \( (J^P) \) as good quantum numbers.
12C(e,e’) cross sections

- Range of three momentum transfer at the QE peak: $100 \text{ MeV} \lesssim |q| \lesssim 1000 \text{ MeV}$

Data from:
Comparison with $(e, e')$ data on $^{12}$C, $^{16}$O, and $^{40}$Ca

- $^{12}$C$(e,e')$ $R_L$ and $R_T$

Data from:

Comparison with (e, e') data on $^{12}$C, $^{16}$O, and $^{40}$Ca

- $^{16}$O(e,e') and $^{40}$Ca(e,e') cross sections

Data from:
Neutrino Cross Sections on $^{12}\text{C}$, $^{16}\text{O}$, $^{40}\text{Ar}$ and $^{56}\text{Fe}$

$A(\nu_\mu, \mu^-)$ cross section (per neutron)

Comparison with Neutrino Data


Comparison with Relativistic Fermi Gas (RFG) model and GENIE

- Electron-nucleus Scattering

\[ q = 95 \text{ [MeV/c]}, \ Q^2 = 0.009 \text{ ([GeV/c])}^2 \]

\[ q = 121 \text{ [MeV/c]}, \ Q^2 = 0.015 \text{ ([GeV/c])}^2 \]

\[ q = 508 \text{ [MeV/c]}, \ Q^2 = 0.242 \text{ ([GeV/c])}^2 \]

\[ q = 675 \text{ [MeV/c]}, \ Q^2 = 0.408 \text{ ([GeV/c])}^2 \]

- CRPA
- RFG
Comparison with Relativistic Fermi Gas (RFG) model and GENIE

- **Electron-nucleus Scattering**

  \[ q = 95 \text{ [MeV/c]}, \quad Q^2 = 0.009 \text{ [(GeV/c)^2]} \]
  
  \[ E = 160 \text{ MeV}, \quad \theta = 36^\circ \]
  
  CRPA
  
  RFG

  \[ q = 508 \text{ [MeV/c]}, \quad Q^2 = 0.242 \text{ [(GeV/c)^2]} \]
  
  \[ E = 560 \text{ MeV}, \quad \theta = 60^\circ \]

- **Neutrino-nucleus Scattering**

  \[ E = 200 \text{ MeV}, \quad \theta = 8^\circ \]

  \[ \nu_{e,\mu} \rightarrow ^{12}\text{C} \]

  GENIEv3.00.06

  - GENIE $\nu_\mu$
  - GENIE $\nu_e$
  - CRPA $\nu_\mu$
  - CRPA $\nu_e$

  \[ q = 121 \text{ [MeV/c]}, \quad Q^2 = 0.015 \text{ [(GeV/c)^2]} \]
  
  \[ E = 200 \text{ MeV}, \quad \theta = 36^\circ \]

  \[ q = 675 \text{ [MeV/c]}, \quad Q^2 = 0.408 \text{ [(GeV/c)^2]} \]
  
  \[ E = 1108 \text{ MeV}, \quad \theta = 37.5^\circ \]
$\nu_e$ to $\nu_\mu$ Cross Section Differences
• At lower energies:
  - For small scattering angles, $\nu_\mu$ cross sections are higher than the $\nu_e$ ones.
  - For larger scattering angles, this behavior is opposite.

• At higher energies:
  - $\nu_e$ and $\nu_\mu$ cross sections roughly coincide.

**$\nu_e$ to $\nu_\mu$ Cross Section Differences**

- Using two independent Mean-Field approaches: RMF and HF-CRPA
  - MF approaches (in a nutshell): All bound and scattering states are obtained by solving the Schrödinger (or Dirac) equation in a central mean field potential. This means all states are consistent and orthogonal. Naturally includes: Binding, Fermi motion, Elastic final state interactions, Pauli blocking, orthogonality (the nucleon wave function does not overlap with a bound state).

- Larger $\nu_\mu$ than $\nu_e$ cross sections for low $\omega$ and $q$ (if the initial and final state wave functions are treated consistently).
  - The muon mass in the final state leads to a larger momentum transfer which shifts the response to larger values.

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Neutrinos Sources and Experiments

\[ K^+ \rightarrow \mu^+ \nu_\mu \text{ (63.4\%)} \]

**Kaon decay at rest**

\( p \rightarrow \text{Target} \)

Magnetic Focusing Horn

\[ \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu \]

236 MeV

10 MeV 100 MeV 1 GeV 10 GeV

\( K^+ \rightarrow \mu^+ \nu_\mu \text{ (63.4\%)} \)
Mono-energetic kaon decay at rest neutrinos

- Mono-energetic neutrino source: kaon decay at rest \( K^+ \rightarrow \mu^+\nu_\mu, E_{\nu_\mu} = 236 \text{ MeV} \)


- Shape-only comparison of several models, too low statistics to discriminate between models
Mono-energetic kaon decay at rest neutrinos


- Exciting near future measurements: MicroBooNE and ICARUS (argon), JSNS$^2$ at J-PARC (carbon)
- Combined analysis of $(e, e')$ and $\nu_\mu$ cross sections can give a strong handle on the axial responses
Neutrinos Sources and Experiments

$p \rightarrow \pi^0 \rightarrow \mu^+ \nu_\mu \\
\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu

Pion decay at rest and Supernova

K. Scholberg
10 ton LAr detector at Lujan center at LANL

- Measure CEvNS cross section on $^{40}\text{Ar}$
- Measure 10s of MeV inelastic CC/NC cross section on $^{40}\text{Ar}$

- Collected data in 2019, analysis ongoing
- Detector is being upgraded, will collect more data in summer 2021
10s of MeV Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

Coherent Elastic

- Tiny recoil energy
- Final state nucleus stays in its ground state
- Signal: keV energy nuclear recoil
- First observed by COHERENT collaboration in 2017
- Opens new window of opportunity to look for weakly interacting new physics at low energies

Inelastic CC/NC

- Small energy transferred to the nucleus
- Nucleus excites to states with well-defined excitation energy, spin and parity ($J^π$). Followed by nuclear de-excitation into gammas, p, n, nuclear fragmentations.

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

CEvNS Cross Section:

$$dσ \propto \frac{G_F^2}{4\pi} Q_W^2 F_W^2(q)$$

Inelastic Cross Section:

$$dσ \propto \frac{G_F^2}{4\pi} \sum_{J^π} [v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_TW_T + v_TW_T']$$
Constraining $^{40}\text{Ar}$ form factor and CEvNS cross section

**Charge Form Factor**

- The $^{40}\text{Ar}$ charge form factor predictions describe experimental elastic electron scattering data well for $q < 2 \text{ fm}^{-1}$.

- For energies relevant for pion decay–at–rest neutrinos, the region above $q > 0.5 \text{ fm}^{-1}$ does not contribute to CEvNS cross section.


**Weak Form Factor**

- Comparison of $^{40}\text{Ar}$ form factor predictions with other calculations.

- Different approaches are based on different representations of the nuclear densities.

Constraining $^{40}$Ar form factor and CEvNS cross section

- Relative CEvNS cross section differences between the results of different calculations:

- Relative CEvNS cross section theoretical uncertainty on $^{40}$Ar (includes nuclear, nucleonic, hadronic, quark levels as well as perturbative errors):


CEvNS experiments at stopped-pion sources are also powerful avenues to measure 10s of MeV inelastic CC and NC cross sections subject to detailed underlying nuclear structure and dynamics.

- These are vital in understanding of core-collapse supernovae, but are almost completely unexplored experimentally so far
- These measurement will greatly enhance the prospects of detecting neutrinos from a core-collapse supernova in future neutrino experiments such as DUNE.

Neutrino signal from the core-collapse supernova starts with a short, sharp “neutronization” (or “breakout”) burst primarily composed of $\nu_e$ from $e^- + p \rightarrow \nu_e + n$. 

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HF-CRPA Model: CC and NC $^{40}$Ar Cross Sections

$^{40}$Ar

$\sigma (cm^2)$

$E (MeV)$

$\sigma (E_\nu (10^{-40}cm^2))$

$E_\nu (MeV)$

$\frac{d\sigma}{d\omega} (10^{-42}cm^2MeV^{-1})$

$\omega (MeV)$

CC ($\nu_e, ^{40}$Ar)

- Total
- $J = 1^-$
- $J = 1^+$
- $J = 2^-$
- $J = 2^+$

NC ($\nu, ^{40}$Ar)

- Total
- $J = 1^-$
- $J = 1^+$
- $J = 2^-$
- $J = 2^+$

$E_\nu = 30$ MeV
$E_\nu = 50$ MeV

44/48
**MARLEY** (Model of Argon Reaction Low Energy Yields) is a neutrino event generator specifically developed to simulate tens-of-MeV neutrino-nucleus interactions in liquid argon.  
Steven Gardiner [arXiv:2010.02393 [nucl-th]].

- An example of MARLEY $\nu_e$ CC event simulated in LArSoft, showing the trajectories and energy deposition points of the interaction products.

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- MARLEY predicts a nearly flat angular distribution (only allowed transitions).

- CRPA includes full expansion of nuclear matrix element as (allowed as well as forbidden transition), predict more backwards strength.
**MARLEY** (Model of Argon Reaction Low Energy Yields) is a neutrino event generator specifically developed to simulate tens-of-MeV neutrino-nucleus interactions in liquid argon. 

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- CRPA implementation in MARLEY is currently on-going, in collaboration with Steven Gardiner.

- Utilizing these simulations in CCM to measure first 10s of MeV CC/NC cross section on $^{40}$Ar. These simulations and measurements will pave the way for supernova physics in DUNE.
These are exciting times. Neutrinos are opening the portal to new frontiers in physics. We are at the beginning of a new era in our understanding of the Universe and a new era of discoveries!

The potential of achieving discovery level precision and fully exploring the physics capabilities of these experiments rely greatly on the precision with which the fundamental underlying process – how does neutrino interact with the target material in the detector – is known. A non-trivial multi-scale, multi-process problem.

I presented some theoretical as well as experimental efforts that tackle this problem from different directions.

Dedicated cross-community efforts and expertise are required to tackle such a problem and establish global constraints on neutrino-nucleus interaction physics that can enable desired precision in neutrino experiments.
Thank you!

https://neutrinos.fnal.gov
Liquid Argon Time Projection Chamber (LArTPC)

Charged particles in LAr produce free ionization electrons and scintillation light.

Ionization charge drifts in a uniform electric field towards the readout wire-planes.

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge].

$m.i.p. \text{ at } 500 \text{ V/cm}: \sim 60,000 \text{ e/cm}$
\sim 50,000 \text{ photons/cm}

Electron drift time $\sim \text{ms}$

VUV photons propagate and are shifted into VIS photons.

Scintillation light fast signals from LDSs give event timing.
Liquid Argon Time Projection Chamber (LArTPC)

- Bubble chamber like imaging
- Fine sampling calorimetry
- Electronic readout
- Scalable to large volumes
SBND will compile data with an unprecedented high event rate due to its proximity to the neutrino source.

It will record millions of events of neutrino interactions on argon, providing world’s highest statistics of neutrino-argon cross section measurements.
In neutrino experiments, we don’t know $\omega$, so let’s look at things through outgoing lepton kinematics. For a given neutrino energy $E_{\nu}$, cross sections as a function of muon energy $T_\mu$, and scattering angle $\theta_\mu$.

- Low $E_{\nu}$: cross section is dominated by low-energy excitations.
- $E_{\nu} = 800$ MeV: forward scattering receive contribution from low-energy excitations.

In general neutrino cross sections are dominated by transverse contribution.

The forward we go in scattering angle, for instance at energies $\sim 800$ MeV, the longitudinal contribution starts competing with the transverse one.

What about flux-folded cross section?

- Cross sections (on $^{12}$C) for a fixed $\cos \theta_\mu = 0.97$ and for fixed neutrino energies from 300 MeV to 1000 MeV, weighted with the T2K $\nu_\mu$ flux and plotted as a function of $p_\mu$.

- Integrating over energies (BNB flux-folded), the peaks disappear but the significant contributions of low-energy excitations ($\omega < 50$ MeV) stays at forward scattering.
