Low-Energy Neutrino-Nucleus Scattering

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Outline

- 10s of MeV Neutrino Sources
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
- Inelastic Neutrino-Nucleus Scattering
- 10s of MeV Physics in GeV-scale Neutrino Beams
Low-Energy Neutrino-Nucleus Scattering

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10s of MeV Neutrino Sources

- Stopped-pion source

\[ p \rightarrow \pi^+ \rightarrow \nu_\mu \]
\[ \sigma(1 \text{ GeV}) \]
\[ \tau \approx 26 \text{ ns} \]
\[ E_{\nu_\mu} = 29.8 \text{ MeV} \]
10s of MeV Neutrino Sources

- **Stopped-pion source**

  ![Diagram](image)

  - $p \rightarrow \pi^+ \rightarrow \mu^+$
  - $\tau \approx 26 \text{ ns}$
  - $E_{\nu_\mu} = 29.8 \text{ MeV}$

- **Coherent CAPTAIN-Mills**

- **Stopped-Pion Neutrino Sources Worldwide**

  - LANSCE/Lujan
  - BNB
  - ISIS
  - CSNS
  - ESS
  - MLF
  - JSNS$^2$
  - SNS
  - FTS/STS

- **Adapted from Kate Scholberg’s talk in the MITP workshop, July 2020**
Neutrino signal from the core-collapse supernova starts with a short, sharp “neutronization” (or “breakout”) burst primarily composed of $\nu_e$ from $e^- + p \rightarrow \nu_e + n$. 

Coherent elastic [CEvNS]

- Tiny recoil energy, large cross section
- Final state nucleus stays in its ground state
- Signal: keV energy nuclear recoil (gammas)

Inelastic CC/NC

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

\[
\sigma (cm^2) = 10^{-38}
\]

\[
E (MeV) = 0 \rightarrow 100
\]

\[
40 Ar
\]

Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

**Coherent elastic [CEvNS]**

\[ \nu_l (E_f, \vec{k}_f) \rightarrow Z^0 (T, \vec{q}) \rightarrow A \mid \Phi_0 \]

\[ \nu_i (E_i, \vec{k}_i) \rightarrow A \mid \Phi_0 \]

**Inelastic CC/NC**

\[ l^-, l^+ / \nu_i, \bar{\nu}_i (E_f, \vec{k}_f) \rightarrow W^\pm / Z^0 (\omega, \vec{q}) \rightarrow X \rightarrow A' \mid \Phi_f \]

\[ \nu_i, \bar{\nu}_i (E_i, \vec{k}_i) \rightarrow A \mid \Phi_0 \]

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

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

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

Transition Amplitude: \[ \mathcal{F}_{n}^\mu = \langle \Phi_0 \mid \hat{J}_{n}^\mu (q) \mid \Phi_0 \rangle \]

Cross Section:

\[ d\sigma \propto \frac{G_F^2}{4\pi} Q_W^2 F_W^2 (q) \]

Cross Section:

\[ d\sigma \propto \frac{G_F^2}{4\pi} \sum_{f_x} \left[ \nu_{CC} W_{CC} + \nu_{CL} W_{CL} + \nu_{LL} W_{LL} \right. \]

\[ + \nu_T W_T \pm \nu_{T'} W_{T'} \]
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Coherent Elastic Neutrino-Nucleus Scattering

COHERENT Collaboration at SNS at ORNL

14 kg CSI detector

**COHERENT Collaboration, Science 357, 6356, 1123–1126 (2017)**

![Graph showing data for Beam OFF and Beam ON](image1)

24 kg LAr (CENNS-10) detector


![Graph showing data for Beam OFF and Beam ON](image2)

Eligio Lisi, NuINT 2018
**CsI: 14.6 kg**

- Flux averaged cross section extracted

  \[
  \text{CEvNS cross section} \quad 169^{+30}_{-26} \times 10^{-40} \text{ cm}^2
  \]

  \[
  \text{SM cross section} \quad 189 \pm 6 \times 10^{-40} \text{ cm}^2
  \]

- Systematic uncertainty reduced from 28% (2017 results) to 13% (2020 results in M7 workshop)

- Detector decommissioned

**\(^{40}\text{Ar}: \text{CENNS-10, 24 kg}\)**

- Flux averaged cross section extracted

  \[
  (2.3 \pm 0.7) \times 10^{-39} \text{ cm}^2
  \]

- Collecting more data

*COHERENT Collaboration, Science 357, 6356, 1123–1126 (2017)*

**Cross section:**

\[
\frac{d\sigma}{dT} = \frac{G_F^2}{\pi} M_A \left[ 1 - \frac{T}{E_i} - \frac{M_A T}{2E_i^2} \right] \frac{Q_W^2}{4} F_W^2(q)
\]

- **Weak Form Factor:**

\[
Q_W \ F_W(q) \approx \langle \Phi_0 | \hat{J}_0(q) | \Phi_0 \rangle \\
\approx (1 - 4 \sin^2 \theta_W) Z F_p(q) - N F_n(q) \\
\approx 2\pi \int d^3r \left[ (1 - 4 \sin^2 \theta_W) \rho_p(r) - \rho_n(r) \right] j_0(qr)
\]

Charge density and charge form factor: proton densities and charge form factors are well known through decades of elastic electron scattering experiments.

Neutron densities and neutron form factor: neutron densities and form factors are poorly known. Note that CEvNS is primarily sensitive to neutron density distributions.
CEvNS Cross Section and Form Factors

**Cross section:**

\[
\frac{d\sigma}{dT} = \frac{G_F^2}{\pi} M_A \left[ 1 - \frac{T}{E_i} - \frac{M_A T}{2E_i^2} \right] \frac{Q_W^2 F_W^2(q)}{4} 
\]

- **Weak Form Factor:**

\[
Q_W F_W(q) \approx \langle \Phi_0 | \hat{J}_0(q) | \Phi_0 \rangle \\
\approx \left( 1 - 4 \sin^2 \theta_W \right) Z F_p(q) - N F_n(q) \\
\approx 2\pi \int d^3r \left[ (1 - 4 \sin^2 \theta_W) \rho_p(r) - \rho_n(r) \right] j_0(qr) 
\]

**Charge density and charge form factor:** Proton densities and charge form factors are well known through decades of elastic electron scattering experiments.

**Neutron densities and neutron form factor:** Neutron densities and form factors are poorly known. Note that CEvNS is primarily sensitive to neutron density distributions.

**Electroweak probes** such as parity-violating electron scattering (PVES) and CEvNS provide relatively model-independent ways of determining weak form factor and neutron distributions.

\[
A_{PV}(q^2) = \frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(q^2)}{ZF_{ch}(q^2)} 
\]

- PVES experiments at JLab: PREX has measured the weak charge of $^{208}\text{Pb}$ at a single value of momentum transfer. PREX–II ($^{208}\text{Pb}$) is underway and CREX ($^{48}\text{Ca}$) is planned.
- Future PVES experiments are planned at MESA (Mainz).
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. Fill up nuclear shells following Pauli principle.

Evaluate proton and neutron density distributions from those wave functions:

\[
\rho_{\tau}(r) = \frac{1}{4\pi r^2} \sum_{\alpha} v_{\alpha,\tau}^2 (2j_\alpha + 1) |\phi_{\alpha,\tau}(r)|^2 \\
(\tau = p, n)
\]

Proton and neutron densities are utilized to calculate proton and neutron form factors:

\[
F_p(q) = \frac{1}{Z} \int d^3 r \, j_0(qr) \rho_p(r), \quad F_n(q) = \frac{1}{N} \int d^3 r \, j_0(qr) \rho_n(r)
\]
**Charge Form Factor**

- Our charge form factor predictions of \( ^{208}\text{Pb} \) describe the elastic electron scattering experimental data remarkably well.


**Weak Form Factor**

- Weak form factor predictions shown along with the single data point measured by the PREX collaboration at a momentum transfer of \( q = 0.475 \text{ fm}^{-1} \).

- The follow–up PREX–II measurement at Jefferson lab aims to reduce the error bars by at least a factor of three.


**Charge Form Factor**

- The $^{40}$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.


- Our calculations compared with Payne *et al.* Phys. Rev. C 100, 061304 (2019) where form factors are calculated within a coupled-cluster theory from first principles using a chiral NNLO_{sat} interaction (See Joanna Sobczyk’s talk today).

**Weak Form Factor**

- Comparison of $^{40}$Ar form factor predictions from four nuclear theory and three phenomenological calculations.

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


- Model of Payne et al. [Phys. Rev. C 100, 061304 (2019)] where form factors are calculated within a coupled-cluster theory from first principles using a chiral NNLO sat interaction.

- Model of Yang et al. [Phys. Rev. C 100, 054301 (2019)] where form factors are predicted within a relativistic mean–field model informed by the properties of finite nuclei and neutron stars.

- Model of Hoferichter et al. [Phys. Rev. D 102, 074018 (2020)] where form factors are calculated within a large-scale nuclear shell model.

- Helm and Klein-Nystrand [adapted by COHERENT] predictions
Relative CEvNS cross section differences between the results of different theoretical calculations.

Comparison with COHERENT CENNS-10 data.

For a full theoretical error estimate see Oleksandr Tomalak’s talk from Tuesday.
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In the inelastic cross section calculations, the influence of long-range correlations between the nucleons is introduced through the continuum Random Phase Approximation (CRPA) on top of the HF-SkE2 approach.

CRPA effects are vital to describe the quasielastic scattering process where the nucleus can be excited to low-lying collective nuclear states.

The local RPA-polarization propagator is obtained by an iteration to all orders of the first order contribution to the particle-hole Green’s function.

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

\[
\frac{d\sigma}{d\omega d\Omega} = \sigma_W E_f k_f \zeta^2(Z', E_f) \left( v_{CC} R_{CC} + v_{CL} R_{CL} + v_{LL} R_{LL} + v_T R_T + \hbar v_T' R_T' \right)
\]

Coulomb correction factor: \( \zeta^2(Z', E_f) \)

\[
\sigma_{WC}^{CC} = \left( \frac{G_F \cos \theta_c}{2\pi} \right)^2, \quad \sigma_{WC}^{NC} = \left( \frac{G_F}{2\pi} \right)^2
\]
Inelastic CC/NC Neutrino-Nucleus Scattering: HF-CRPA Model
MARLEY (Model of Argon Reaction Low Energy Yields) is a dedicated low-energy neutrino event generator developed by Steven Gardiner to simulate tens-of-MeV neutrino-nucleus interactions on argon.

**MARLEY** (Model of Argon Reaction Low Energy Yields) is a dedicated low-energy neutrino event generator developed by Steven Gardiner to simulate tens-of-MeV neutrino-nucleus interactions on argon.


- Fermi gas-based approximation, hence “traditional” neutrino generators, are inadequate at these energies where low-energy excitations, giant resonances and a handle on the de-excitation $\gamma$-rays play the central role.

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

- Dedicated low-energy generators are needed.

  newton ($^{16}$O) B. Bodur, https://github.com/itscubist/newton
**Inelastic CC/NC Neutrino-Nucleus Scattering: MARLEY Generator**

- **MARLEY** (Model of Argon Reaction Low Energy Yields) is a dedicated low-energy neutrino event generator developed by Steven Gardiner to simulate tens-of-MeV neutrino-nucleus interactions on argon.


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


\[
E_\nu = 16.3 \text{ MeV}
\]

[Diagram showing Inelastic Neutrino-Nucleus Scattering]
• **MARLEY Cross Section Model:** two-step process

  I. Inclusive scattering on the nucleus:

  \[
  \frac{d\sigma}{d\cos\theta_\ell} = \frac{G_F^2 |V_{ud}|^2}{2\pi} \frac{E_i E_f}{s} |p_{\ell}| \left[ \left(1 + \beta_\ell \cos \theta_\ell \right) B(F) + \left(1 - \frac{1}{3} \beta_\ell \cos \theta_\ell \right) B(GT) \right]
  \]

  Allowed approximation (long–wavelength ($q \to 0$) and slow nucleons ($p_N/m_N \to 0$) limit), Fermi and Gamow-Teller matrix elements:

  \[
  B(F) \equiv \frac{g_V^2}{2J_i + 1} \left| \langle J_f \parallel O_F \parallel J_i \rangle \right|^2 \quad B(GT) \equiv \frac{g_A^2}{2J_i + 1} \left| \langle J_f \parallel O_{GT} \parallel J_i \rangle \right|^2
  \]

  based on a combination of indirect measurements (e.g., $\beta$ decay) and a QRPA calculation
II. Nuclear de-excitation:

For bound nuclear states, the de-excitation gamma rays are sampled using tables of experimental branching ratios.

For unbound nuclear states, MARLEY simulates the competition between gamma-ray and nuclear fragment emission using the Hauser-Feshbach statistical model.

Differential decay width for emission of nuclear fragment $\alpha$ ($A \leq 4$ considered) or a $\gamma$-ray:

\[
\frac{d\Gamma_{\alpha}}{dE'_{\alpha}} = \frac{1}{2\pi \rho_i(E_x, J, \Pi)} \sum_{\ell=0}^{\infty} \sum_{j=|\ell-s|}^{\ell+s} \sum_{J'=|J-j|}^{J+j} T_{\ell j}(\varepsilon) \rho_f(E'_{\alpha}, J', \Pi')
\]

\[
\frac{d\Gamma_{\gamma}}{dE'_{\gamma}} = \frac{1}{2\pi \rho_i(E_x, J, \Pi)} \sum_{\lambda=1}^{\infty} \sum_{J'=|J-\lambda|}^{J+\lambda} \sum_{\Pi' \in \{-1, 1\}} T_{X\lambda}(E_{\gamma}) \rho_f(E'_{\gamma}, J', \Pi')
\]
\section*{CRPA and MARLEY}

\textbullet{} \textbf{Allowed and forbidden transitions}

- MARLEY (only allowed transitions, Fermi and Gamow-Teller matrix elements) predicts a nearly flat angular distribution.

- CRPA includes full multipole expansion of nuclear matrix element (allowed as well as forbidden transitions), predict more backwards strength.
CRPA and MARLEY

- Allowed and forbidden transitions

MARLEY predicts that neutrons have a relatively small contribution to the overall "energy budget" at high energies. An artifact of the allowed approximation which underestimates the strength at high excitation energies.

CRPA and MARLEY

- CRPA implementation in MARLEY is on-going.
- Implementing inclusive nuclear response from CRPA predictions, and utilizing MARLEY’s de-excitation model to predict energies of the final state particles.

\[ ^{16}O \] example:

\[ ^{40}Ar \] implementation is in progress.
**Coherent CAPTAIN Mills at LANL:** 10 ton LAr detector at Lujan center at LANL. Collected data in 2019, analysis ongoing. Detector is being upgraded, gearing up to collect more data in the summer 2021. Stay tuned! See [Tyler Thornton’s talk at Magnificent CEvNS 2020](#).
Inelastic CC/NC Neutrino-Nucleus Scattering: Near-Future Measurements

- **Coherent CAPTAIN Mills at LANL**: 10 ton LAr detector at Lujan center at LANL. Collected data in 2019, analysis ongoing. Detector is being upgraded, gearing up to collect more data in the summer 2021. Stay tuned! See *Tyler Thornton’s talk at Magnificent CEvNS 2020*.

- **COHERENT at SNS**: COH-Ar-10 (24kg) LAr detector, see Erin Conley’s talk from Tuesday. COH-Ar-750 (750 kg) LAr detector is underway. Iodine (NaIvE) and Pb, Fe, Cu (NIN cubes) detectors.

- **JSNS² at JPARC-MLF**: 50 ton gd-loaded LS detector.

- **10s of MeV electron scattering experiment is planned at MESA, Mainz**: see Luca Doria’s talk from Wednesday.
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At forward scattering angles (low momentum transfer), the neutrino-nucleus cross section at GeV-scale energies is impacted by the same nuclear physics effects that are important for the low-energy case more generally.

At these kinematics, differences between final-state lepton masses become vital and affect the ratio of the charged-current $\nu_e$ to $\nu_\mu$ cross sections.
Experimental observation of CEvNS opened a new portal of searching weakly interacting new physics at low energies. Entire nuclear dynamics in CEvNS process is embedded in the weak form factor which is not well constrained.

- Microscopic calculations, future precise measurements of CEvNS cross section and PVES asymmetry measurements will enable precise determination of weak form factor and neutron distributions.

CEvNS experiments at stopped-pion sources are powerful avenues to measure 10s of MeV inelastic CC and NC neutrino-nucleus cross sections.

- These measurements will play a vital role in enhancing future long baseline neutrino experiments’ capability of detecting core-collapse supernovae neutrinos.

- 10s of MeV electron-nucleus scattering cross sections at MESA will pave the way in constraining nuclear model at these energies.

We presented a consistent description of both coherent elastic and inelastic neutrino-nucleus scattering within a unified nuclear theory approach.

- The model is currently being implemented in the dedicated low-energy neutrino event generator, MARLEY, for wider use.
Back-up
MeV-scale Physics in GeV-scale Beams

“Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT”
