Neutrino cross-sections theory

Noemi Rocco

August 5th, 2021
Addressing Neutrino-Oscillation Physics

\[ P_{\nu_\mu \rightarrow \nu_e}(E, L) \sim \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \rightarrow \Phi_e(E, L)/\Phi_\mu(E, 0) \]

Detectors measure the **neutrino interaction rate**:

\[ N_e(E_{\text{rec}}, L) \propto \sum_i \Phi_e(E, L) \sigma_i(E) f_{\sigma_i}(E, E_{\text{rec}}) dE \]

- Reconstructed \( \nu \) energy
- Cross Section
- Smearing matrix

A precise determination of \( \sigma(E) \) is crucial to extract \( \nu \) oscillation parameters
To study neutrinos we use nuclei

Neutrino scattering extensively studied 1970-90’s using deuterium-filled **bubble chambers**

\[ \mathcal{N}_{\text{hits}} = \sigma \times \Phi \times N \]

# Targets

Utilize **heavy target** in neutrino detectors to maximize interactions \( \rightarrow \) understand **nuclear structure**

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**Carbon**

MiniBooNE

**NOvA**

MINERvA

**Oxygen**

S-K

**Argon**

MicroBooNE

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Noemi Rocco, nrocco@fnal.gov
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Unprecedented accuracy in the determination of neutrino-argon cross section is required to achieve design sensitivity to CP violation at DUNE.

Current oscillation experiments report large systematic uncertainties associated with the neutrino-nucleus interaction models.

Nuclei are complicated objects. Many different reaction mechanisms:

- **QE**
  - Reaction: $\nu + p \rightarrow \mu^- + n$
  - Probability: $|U_{\nu e}|^2$

- **MEC**
  - Reaction: $\nu + n \rightarrow \mu^- + p$
  - Probability: $|U_{\nu e}|^2$

- **RES**
  - Reaction: $\nu + p \rightarrow \mu^- + n + \pi^+$
  - Probability: $|U_{\nu e}|^2$

- **DIS**
  - Reaction: $\nu + p \rightarrow \mu^- + p + n$
  - Probability: $|U_{\nu e}|^2$

Theory of lepton-nucleus scattering

- The cross section of the process in which a lepton scatters off a nucleus is given by

\[ d\sigma \propto L^{\alpha \beta} R_{\alpha \beta} \]

Leptonic Tensor: can include new physics models

Hadronic Tensor: nuclear response function

The initial and final wave functions describe many-body states:

\[ |0\rangle = |\Psi_0^A\rangle, |f\rangle = |\Psi_f^A\rangle, |\psi_p^N, \Psi_f^{A-1}\rangle, |\psi_{\pi^k}, \psi_p^N, \Psi_f^{A-1}\rangle \ldots \]

One and two-body current operators

\[ \begin{align*}
\begin{array}{c}
\text{Diagram 1} \\
\text{Diagram 2}
\end{array}
\end{align*}
\]
Nuclear many-body theory

Neutrino experiments are becoming more and more sensitive to the complexity of nuclear dynamics.

Same starting point for different many-body methods: Effective Field Theory interactions and currents

\[ H = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots \]

- Green’s Function Monte Carlo
- Spectral Function (SF)
- Short-time Approximation (STA)

Argonne
Cross sections: Green’s Function Monte Carlo

GFMC accurately obtain the properties of nuclei to $^{12}\text{C}$ using high performance computing

**Exact results** for $v$-cross sections in the quasi-elastic region up to moderate values of $q$.


Limitations: high energy regions, pions can not be explicitly included
Cross sections: Spectral function approach

The intrinsic properties of the nucleus are described by the Spectral Function → effective field theory and nuclear many-body methods

\[ |f\rangle \rightarrow |p\rangle \otimes |f_{A-1}\rangle \]

\[ d\sigma_A = \int dE d^3k \ d\sigma_N P(k, E) \]

High energy and momentum correlated pairs

Observed dominance of np-over-pp pairs for a variety of nuclei
Spectral function formalism: unified framework able to describe the different reaction mechanisms retaining an accurate treatment of nuclear dynamics

- NR, S. Gardiner, M. Betancourt working on efficiently implementing the spectral function model in GENIE

NR, Frontiers in Phys. 8 (2020) 116

\[ E_e = 730 \text{ MeV}, \theta_e = 37.0^\circ \]

Using electron scattering data to validate our predictions for \(^{40}\text{Ar}\)

NR, J. Isaacson, S. English (SULI program) predictions for the DIS region convoluting spectral function+nucleon pdf
Comparing different many-body methods

• $e^{-3H}$: inclusive cross section

NR, A. Lovato, S. Pastore, et al, in preparation

Comparisons among QMC, SF, and STA approaches: first step to precisely quantifying the uncertainties inherent to the factorization of the final state.

• Gauge the role of relativistic effects in the energy region relevant for neutrino experiments.
A Quantum Monte Carlo based cascade

We investigated the role of nuclear effects in intra-nuclear cascade


The nucleons’ positions are sampled from 36000 GFMC configurations.

Check interaction: accept-reject test with a cylinder probability distribution.

- We computed different observables: p-12C cross section, 12C transparency and obtained a fair agreement with data
- Extend the model to include pion degrees of freedom and compare with exclusive observables.
Lattice QCD and neutrino-nucleus

- First LQCD calculation using staggered fermions of nucleon axial charge $g_A$

Deep Inelastic Scattering

- First LQCD calculation of quark momentum fractions of nuclei

Two nucleon currents

- Exploratory LQCD calculations of axial matrix elements governing triton $\beta$-decay performed at second, lighter quark mass
Several **systematic uncertainties** of nuclear matrix element calculations still need to be quantified

- Heavier than physical quark masses only
- One lattice spacing
- Finite size effects

Excited-state effects can be large in LQCD calculations of nuclei, because **energy gaps** between bound states and finite-volume “scattering” states are small vs $\Lambda_{\text{QCD}}$

Reliable but computationally challenging **variational method** — diagonalize correlation-function matrix involving many different creation/annihilation operator structures

Work in progress to understand excited-state effects for $NN$ using variational method

  Wagman and collaborators (NPLQCD++), arXiv:2108.xx

Similar tools can be applied to $N\pi$ resonance production and elastic nucleon axial form factors

  Jay, Wagman, and collaborators, *in progress*
Double Bang events from New Physics at DUNE

- New physics models allows for neutrinos to up-scatter into heavier neutrino states $N$

First bang: neutrino-nucleus interaction, production of heavy neutrino

Second bang: decay of heavy neutrino after propagating for some distance

- The number of DB events depend on the $v$-nucleus cross section and the probability for the heavy neutrino to decay after traveling for a distance $L$


- Expected sensitivity to the transition magnetic moment $\nu\mu - N$ from DBs signals in the DUNE LAr near detector

More work on this topic: Harnik, Machado, Plestid, Brdar

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Low energy effects in CC cross sections

- **Coulomb corrections**: R. Plestid, O. Tomalak, R. H.J. Hill, in progress

  A charged lepton produced in a CC interaction experiences a Coulomb potential from the remnant nucleus, this effect is \( \propto Z \alpha \)

  Currently handled by GENIE a Distorted Wave treatment based on J. Engel, PRC 57, 1998

  Impact of this effect: extra asymmetry cross sections, altered lepton kinematics, shift effective momentum of the nuclear response functions


  Radiative corrections crucial for % level oscillation program

  Effect is relevant also in the nuclear case

Radiative corrections to neutrino-nucleon interactions at LO are included in the factorization framework. Detailed calculations of cross sections for various experimental conditions.
Simulate neutrino-nucleus interactions to untangle neutrino oscillations from the measured interactions.