Historical Review and Future Program for Neutrino Cross-Section Measurements and Calculations

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Outline

- Why cross sections are relevant for neutrino oscillation
- Past and present measurements of neutrino cross sections
- Theoretical models of neutrino cross sections
- Future program for neutrino cross section measurements and calculations
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:

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

A quantitative knowledge of \( \sigma(E) \) and \( f_\sigma(E) \) is crucial to precisely extract \( \nu \) oscillation parameters.
To study neutrinos we need nuclei

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

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

# Targets

Utilize heavy target in neutrino detectors to maximize interactions → understand nuclear structure

**Carbon**

**Oxygen**

**Argon**

**Bubble Chamber experiment at Fermilab**

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[Image of bubble chambers]

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Lepton-nucleus cross section

Different reaction mechanisms contributing to lepton-nucleus cross section—fixed value of the beam energy (monochromatic)

\[
\frac{d\sigma}{d\Omega dE'}
\]

\(\omega_e \sim \frac{q^2}{2m}\)

\(\omega\) Energy transfer

In neutrino experiments these contributions are not nicely separated.
Energy distribution of neutrino fluxes

Present to Future: T2K, MicroBooNE, Nova, MINERvA, Hyper-Kamiokande, DUNE

Figure 3. Muon neutrino and muon anti-neutrino flux predictions from current and future accelerator based neutrino experiments. Here, the top two plots are neutrino mode beam muon neutrino flux predictions, where the bottom two plots are anti-neutrino mode beam muon anti-neutrino flux predictions. Predictions are all arbitrary normalized. Left plots are current experiments (T2K, MiniBooNE, MINERvA with low energy NuMI), and right plots are current to future experiments (Hyper-Kamiokande, MicroBooNE, NOvA, DUNE, MINERvA with medium energy NuMI).

- MINERvA, MINOS, and NOvA use NuMI neutrino beamline. The two important flux configurations are low energy (LE) mode and medium energy (ME) mode. Also, detector configurations can be on-axis or off-axis. Here, MINOS and MINERvA are both LE and ME on-axis experiments, and NOvA is a ME off-axis experiment, and their flux predictions are quite different. Note MINERvA does not provide neutrino flux below 1.5 GeV where flux systematic errors have not been evaluated yet.

- DUNE will use a dedicated beamline, which will have a wide-band beam to measure neutrino oscillations not only the first maximum, but also the second oscillation maximum [165].

- Hyper-Kamiokande uses higher power J-PARC off-axis neutrino beam [14], and here we simply assumed the same shape with current T2K J-PARC off-axis neutrino beam.

The on-axis beam experiments, such as MiniBooNE, MINERvA, and DUNE have a wider beam spectrum, and off-axis beam experiments, such as T2K and NOvA have narrower spectrums. Although spectra are narrower for off-axis beams, they have long tails going to higher energy. This is a standard feature for off-axis beams. Therefore understanding of neutrino interactions are important in all 1-10 GeV spectrum for both on-axis and off-axis beam experiments.

Figure 4 shows more detailed neutrino flux predictions. Here, we use T2K neutrino

In MiniBooNE data analysis, an event is labeled as CCQE if no final state pions are detected in addition to the outgoing muon.

First measurement of the double differential cross section for CCQE scattering on $^{12}$C

To explain the data careful evaluation of nuclear effects was required: multi-nucleon emission first identified.
The T2K experiment data-taking started in January 2010 and continues in 2020 and beyond. The dominant process at the peak energy of \( \sim 0.6 \text{ GeV} \) is CCQE scattering.

Simultaneous measurement of \( \nu_\mu \text{-CC0}\pi \) cross section on oxygen and carbon.

\( \text{arXiv:2004.05434} \)

First CC\( \pi^+ \) results on water
MINERvA

MINERvA is the first neutrino experiment in the world to use a **high-intensity beam** to study neutrino reactions with a **variety of nuclei**: He, C, O, Pb and Fe. Strongly constraints neutrino interactions

Fine-grained scintillator tracker allows to identify and precisely measure outgoing protons and μ. Probe **nuclear effects** using the transverse imbalance of \( p \) and \( \mu \)


Full double differential cross section projected using the kinematics of the \( \mu \):

NOvA

The neutrino flux in the NOvA ND is a narrow band beam peaked at 1.9 GeV, between 1.1 and 2.8 GeV.

Cross section modeling is one of the leading systematic uncertainties for NOvA's measurements.

![Cross section modeling graph]

NC coherent π0 production on a carbon:

\[ \sigma(\text{COH} \, \pi^0) \times 10^{40} \text{cm}^2/\text{Nucleus} \]

\[ \nu + A \rightarrow \nu + A + \pi^0 \]

\[ \nu + A \rightarrow \mu + \pi^0 + X \]

3.72x10^{20} POT

Shape Only

Data / GENIE

\[ \frac{d\sigma}{dp_{\pi}} \text{[Arbitrary Units]} \]

Neutrino Energy (GeV)

\[ p_{\pi} \text{[GeV/c]} \]

Source: S.K. Lin's talk @ SUSY 2019

arXiv:1902.00558
MicroBooNE

Multiple LAr-TPC detectors at different baselines along the Booster Neutrino Beam will search for high $\Delta m^2$ neutrino oscillation: resolve the source MiniBooNE low energy excess

MicroBooNE precision measurements $\nu$-$\text{Ar}$ cross sections in the hundreds-of-MeV to few-GeV energy range

Multiple proton emission

First measurement of $\nu_\mu$ CC double-differential inclusive cross sections on Ar at $<E_\nu> = 0.8$ GeV

Important test for: nuclear physics model for multi-nucleon emission and event generator predictions for proton multiplicity and kinematics

Provides a test for the details of neutrino cross section models

$\nu_\mu$ CC double-differential inclusive cross section on Ar at $<E_\nu> = 0.8$ GeV

Theory of lepton-nucleus scattering

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

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

\[ |0\rangle = |\Psi_0^A\rangle, |f\rangle = |\Psi_f^A\rangle, |\psi^N_p, \Psi_f^{A-1}\rangle, |\psi^\pi_k, \psi^N_p, \Psi_f^{A-1}\rangle \ldots \]

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

One and two-body current operators
Global Fermi gas: independent particles

Protons and neutrons are considered as moving freely within the nuclear volume.

Simple picture of the nucleus: only statistical correlations are retained (Pauli exclusion principle).

The energy of the highest occupied state is the Fermi energy: \( E_F \), \( B' \) constant binding energy.

The Global Fermi gas model has been widely used in comparisons of neutrino scattering data.

MiniBooNE data analysis to reproduce the data: \( M_A \sim 1.35 \text{ GeV} \) is incompatible with former measurements in bubble chamber: \( M_A \sim 1.03 \text{ GeV} \)

Nuclear effects can explain the axial mass puzzle.
Valencia - Lyon models

This approach allows for a unified treatment of different reaction mechanisms

QE, two-nucleon emission, π-production are obtained performing different cuts on the internal lines of the W-boson self energy:

Optical theorem
Valencia - Lyon models

Multi-nucleon emission first proposed as a solution of the MiniBooNE axial-mass puzzle in Martini et al, PRC 80, 065501 (2009)

The Valencia and Lyon model have been tested in the CCQE-like, CC0π and CC inclusive data for different experiments

They are currently implemented in different EG

The inclusion of RPA effects more relevant at low-\(q^2\) yielding shape distortion in the QE cross section
SuSusav2 model

**SuSA** utilizes the longitudinal scaling function extracted from electron scattering data to obtain both electron and neutrino cross sections

**Relativistic Mean Field (RMF):** more rigorous approach to compute the scaling functions. Reproduces the $T$ enhancement displayed by data and incorporates final state interactions but limited to intermediate kinematics.

**SuSusav2:** provides a description of the responses based on RMF behavior at lower $q$, while for higher $q$ it mimics RPWIA trends.

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![Graph showing scaling functions](image)

**J.A. Caballero et al, Phys.Lett.B.653, 2007**

**Meson Exchange Currents:** 2p2h included is based on a RFG calculation with fully relativistic currents

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G.D. Megias et al, PRD.91.073004
SuSav2 model

Extensive comparison with electron scattering data $^{12}$C(e,e') double differential cross section

$\theta$ \quad $\mu$

$\sigma$ (cm$^2$ Nucleon$^{-1}$ GeV$^{-1}$)

$0.9 < \cos(\theta_{\mu}) < 0.94$

SuSA-v2

Comparison of the T2K CC0π measurement of νμ-C with the SuSAv2 and Valencia models each with an additional pion-absorption contribution as implemented in GENIE.


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
Green’s Function Monte Carlo

GFMC accurately solves the Schrödinger equation for nuclei up to $^{12}$C using high performance computing

**Virtually exact results** for nuclear electroweak responses in the quasi-elastic region up to moderate values of $q$. Initial and final state interactions fully accounted for.

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T2K flux is the most suitable one for the GFMC calculations (nonrelativistic)
Short Time Approximation

The STA method utilizes QMC techniques to predict the response function of nuclei in the quasielastic region.

Assumption: for short times (moderate $\mathbf{q}$) only the active pair of nucleons propagate

Interaction effects at the two-nucleon level are fully retained, and the interference between one- and two-body terms are consistently accounted for, access to exclusive channels

Electromagnetic responses of $^4\text{He}$:

\[ R_T(\omega, q) \text{ [MeV$^{-1}$]} \]

\[ R(\omega, q) \text{ [MeV$^{-1}$]} \]

\[ q=500 \text{ MeV/c} \]

\[ 0 \text{ to } 300 \text{ MeV} \]

\[ 0 \text{ to } 0.025 \text{ MeV$^{-1}$} \]

\[ 0 \text{ to } 0.005 \text{ MeV$^{-1}$} \]

\[ 0 \text{ to } 0.01 \text{ MeV$^{-1}$} \]

Factorization Scheme and Spectral Function

For sufficiently large values of $|q|$, the **factorization scheme** can be applied.

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

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

Factorization Scheme and Spectral Function

Spectral function formalism including the **one-** and **two-body current** contributions and the **pion production** amplitudes (ANL-Osaka model) for electron and neutrino $^{12}$C-scattering

Preliminary comparison with CC0π data on $^{12}$C from MINERvA using $\mu$ kinematics. Only the one body current operator has been included. Next steps: inclusion of MEC and π production and absorption
Future experiments and theory efforts

DUNE and Hyper-K high-precision measurement of neutrino oscillation parameter → accurate cross section predictions supplemented by theoretical uncertainty

Hyper-K

DUNE

Electron for Neutrinos:
constrain interaction models used in $\nu$ energy reconstruction

Jlab E12-14-012 experiment:
study the properties of Ar nucleus by electron scattering. The data cover different reaction mechanisms

QE-RES: rich set of new cross section measurements T2K, MINERvA, NOvA, MicroBooNE

DIS: data and new analyses from MINERvA on different nuclei
Future experiments and theory efforts


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Theoretical uncertainty estimate: truncation of the chiral expansion and statistical uncertainty of the ab-initio method

Using more approximate methods, first calculations of lepton-Ar cross sections

Controlled approximation of the nuclear-many body problem are needed to include relativistic effects. Benchmark with ab-initio results

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C. Barbieri, NR, V. Somà, PRC 100 (2019) 6, 062501
Thank you for your attention!