From eV to EeV: Neutrino cross sections across energy scales

| Citation       | Formaggio, J., and G. Zeller. “From eV to EeV: Neutrino Cross Sections Across Energy Scales.” Reviews of Modern Physics 84.3 (2012): 1307–1341. © 2012 American Physical Society |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| As Published   | http://dx.doi.org/10.1103/RevModPhys.84.1307                                                                                                                                                  |
| Publisher      | American Physical Society                                                                                                                                                                      |
| Version        | Final published version                                                                                                                                                                        |
| Citable link   | http://hdl.handle.net/1721.1/75437                                                                                                                                                             |
| Terms of Use   | Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.                                      |
From eV to EeV: Neutrino cross sections across energy scales

J. A. Formaggio*

Laboratory for Nuclear Science Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

G. P. Zeller†

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

(published 24 September 2012)

Since its original postulation by Wolfgang Pauli in 1930, the neutrino has played a prominent role in our understanding of nuclear and particle physics. In the intervening 80 years, scientists have detected and measured neutrinos from a variety of sources, both man made and natural. Underlying all of these observations, and any inferences we may have made from them, is an understanding of how neutrinos interact with matter. Knowledge of neutrino interaction cross sections is an important and necessary ingredient in any neutrino measurement. With the advent of new precision experiments, the demands on our understanding of neutrino interactions is becoming even greater. The purpose of this article is to survey our current knowledge of neutrino cross sections across all known energy scales: from the very lowest energies to the highest that we hope to observe. The article covers a wide range of neutrino interactions including coherent scattering, neutrino capture, inverse beta decay, low-energy nuclear interactions, quasielastic scattering, resonant pion production, kaon production, deep inelastic scattering, and ultrahigh energy interactions. Strong emphasis is placed on experimental data whenever such measurements are available.

DOI: 10.1103/RevModPhys.84.1307 PACS numbers: 25.30.Pt, 13.15.+g, 14.60.Lm

CONTENTS

I. INTRODUCTION 1307

II. A simple case: Neutrino-lepton scattering 1308
   A. Formalism: Kinematics 1308
   B. Formalism: Matrix elements 1309
   C. Experimental tests of electroweak theory 1311
   D. Radiative corrections and \( G_F \) 1312

III. Thresholdless processes: \( E \sim 0–1 \text{ MeV} \) 1312
   A. Coherent scattering 1312
   B. Neutrino capture on radioactive nuclei 1313

IV. Low-energy nuclear processes: \( E \sim 1–100 \text{ MeV} \) 1313
   A. Inverse beta decay 1314
   B. Beta decay and its role in cross section calibration 1314
   C. Theoretical calculations of neutrino-deuterium cross sections 1315
   D. Other nuclear targets 1316
   E. Estimating Fermi and Gamow-Teller strengths 1317
   F. Experimental tests of low-energy cross sections on nuclei 1318
      1. Hydrogen 1318
      2. Deuterium 1320
      3. Additional nuclear targets 1320
   G. Transitioning to higher energy scales 1322

V. Intermediate energy cross sections: \( E \sim 0.1–20 \text{ GeV} \) 1322
   A. Quasielastic scattering 1324
   B. NC elastic scattering 1326
   C. Resonant single pion production 1327
   D. Coherent pion production 1331
   E. Multipion production 1331

VI. High-energy cross sections: \( E \sim 20–500 \text{ GeV} \) 1333
    A. Deep inelastic scattering 1333

VII. Ultra-high-energy neutrinos: 0.5 TeV–1 EeV 1335
    A. Uncertainties and projections 1336

VIII. Summary 1337

Acknowledgments 1337
References 1337

I. INTRODUCTION

The investigation into the basic properties of the particle known as the neutrino has been a particularly strong and active area of research within nuclear and particle physics. Research conducted over the latter half of the 20th century has revealed, for example, that neutrinos can no longer be considered as massless particles in the standard model, representing perhaps the first significant alteration to the theory. Moving into the 21st century, neutrino research continues to expand in new directions. Researchers further investigate the nature of the neutrino mass or explore whether neutrinos can help explain the matter-antimatter asymmetry of the Universe. At the heart of many of these experiments is the need for neutrinos to interact with other standard model particles. An understanding of these basic interaction cross sections is often an understated but truly essential element of any experimental neutrino program.

The known reactions of neutrinos with matter fall completely within the purview of the standard model of particle physics. The model of electroweak interactions govern what those reactions should be, with radiative corrections that can be
accurately calculated to many orders. As such, our goal in this review is essentially already complete: we would simply write down the electroweak Lagrangian and we would be finished. Of course, in practice this is very far from the truth. As with many other disciplines, many factors compound our simple description, including unclear initial-state conditions, subtle-but-important nuclear corrections, final-state interactions, and other effects. One quickly finds that theoretical approximations which work well in one particular energy regime completely break down elsewhere. Even the language used in describing certain processes in one context may seem completely foreign in another. Previous neutrino experiments could avoid this issue by virtue of the energy range in which they operated; now, however, more experiments find themselves “crossing boundaries” between different energy regimes. Thus, the need for understanding neutrino cross sections across many decades of energy is becoming more imperative. To summarize our current collective understanding, this work provides a review of neutrino cross sections across all explored energy scales. The range of energies covered, as well as their relevance to various neutrino sources, is highlighted in Fig. 1. We first establish the formalism of neutrino interactions by considering the simplest case of neutrino-electron scattering. Our focus will then shift to neutrino interaction cross sections at low (1–100 MeV), intermediate (0.1–20 GeV), high (20–500 GeV), and ultrahigh (0.5 TeV–1 EeV) energies, emphasizing our current theoretical and experimental understanding of the processes involved. Though it may be tempting to interpret these delineations as hard and absolute, they are only approximate in nature, meant as a guide for the reader.

II. A SIMPLE CASE: NEUTRINO-LEPTON SCATTERING

A. Formalism: Kinematics

We begin with the simplest of neutrino interactions, neutrino-lepton scattering. As a purely leptonic interaction, neutrino-lepton scattering allows us to establish the formalism and terminology used through the paper, without introducing some of the complexity that often accompanies neutrino-nuclear scattering. The general form of the two-body scattering process is governed by the dynamics of the process encoded in the matrix elements and the phase space available in the interaction. Figure 2 shows the tree-level diagram of a neutrino-lepton charged current interaction, known as inverse muon decay. A muon neutrino with four-momentum \( p_\nu \) (aligned along the \( z \) direction) scatters in this example with an electron with four-momentum \( p_e \), which is at rest in the laboratory frame. This produces an outgoing muon with four-momentum \( k_\mu \) and a scattered electron neutrino with four-momentum \( k_\nu \). In the laboratory frame, the components of these quantities can be written as

\[
p_\nu = (E_\nu, \hat{p}_\nu), \quad k_\mu = (E_\mu, \vec{k}_\mu).
\]

\[
p_e = (m_e, 0), \quad k_\nu = (E_\nu, \vec{k}_\nu).
\]

Here we use the convention of the zeroth component corresponding to the energy portion of the energy-momentum vector, with the usual energy-momentum relation \( E_i^2 = |\vec{k}_i|^2 + m_i^2 \). From these four-vector quantities, it is often useful to construct new variables which are invariant under Lorentz transformations:

\[
s = (p_\nu + p_e)^2 \quad \text{(center of mass energy)},
\]

\[
Q^2 = -q^2 = (p_\nu - k_\mu)^2 \quad \text{(4-momentum transfer)},
\]

\[
y = \frac{p_e \cdot q}{p_e \cdot p_\nu} \quad \text{(inelasticity)}.
\]

In the case of two-body collisions between an incoming neutrino and a (stationary) target lepton, the cross section is given in general by (\( \hbar = c = 1 \)) (Berestetskii, Lifshitz, and Pitaevski, 1974),

\[\text{FIG. 1 (color online). Representative example of various neutrino sources across decades of energy. The electroweak cross section for } \bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \text{ scattering on free electrons as a function of neutrino energy (for a massless neutrino) is shown for comparison. The peak at } 10^{16} \text{ eV is due to the } W^- \text{ resonance, which we discuss in greater detail in Sec. VII.}\]
The full description of the interaction is encoded within the matrix element $M$. The standard model readily provides a prescription to describe neutrino interactions via the leptonic charged weak current $j^{\mu}_{W}$, known as inverse muon or inverse tau decays) one finds

$$j^{\mu}_{W} = 2 \sum_{a=e,\mu,\tau} \bar{\nu}_{aL} \gamma^{\mu} l_{aL}.$$  

(5)

The second type of interaction, known as the neutral-current (NC) exchange, is similar in character to the charged current case. The leptonically charged weak current $j^{\mu}_{W}$, describes the exchange of the neutral boson, $Z^{0}$,

$$j^{\mu}_{Z} = 2 \sum_{a=e,\mu,\tau} g^{\mu}_{F} \bar{\nu}_{aL} \gamma^{\mu} v_{aL} + g^{\mu}_{Z} l_{aL} \gamma^{\mu} l_{aR} + g^{\mu}_{R} \bar{\nu}_{aR} \gamma^{\mu} l_{aR}.$$  

(6)

Here $\nu_{aL(R)}$ and $l_{aL(R)}$ correspond to the left (right) neutral and charged leptonic fields, while $g^{\mu}_{F}$, $g^{\mu}_{Z}$, and $g^{\mu}_{R}$ represent the fermion left- and right-handed couplings (for a list of these values, see Table I). Though the charged leptonic fields are of a definite mass eigenstate, this is not necessarily so for the neutrino fields, giving rise to the well-known phenomena of neutrino oscillations.

Historically, the neutrino-lepton charged current and neutral-current interactions have been used to study the nature of the weak force in great detail. We now return to the case of calculating the charged and neutral-current reactions. These previously defined components enter directly into the Lagrangian via their coupling to the heavy gauge bosons, $W^{\pm}$ and $Z^{0}$,

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} (j^{\mu}_{W} W^{\mu}_{\nu} + j^{\mu}_{Z} Z^{\mu}_{\nu}),$$  

(7)

$$\mathcal{L}_{NC} = -\frac{g}{2\cos\theta_{W}} j^{\mu}_{Z} Z^{\mu}_{\nu}.$$  

(8)

Here $W_{\nu}$ and $Z_{\nu}$ represent the heavy gauge boson field, $g$ is the coupling constant while $\theta_{W}$ is the weak mixing angle. It is possible to represent these exchanges with the use of Feynman diagrams, as is shown in Fig. 3. Using this formalism, it is possible to articulate all neutrino interactions (’t Hooft, 1971) within this simple framework.

We begin by looking at one of the simplest manifestations of the above formalism, where the reaction is a pure charged current interaction

$$\nu_{\mu} + e^{-} \rightarrow l^{-} + \nu_{e} \quad (l = \mu \text{ or } \tau).$$  

(9)

The corresponding tree-level amplitude can be calculated from the above expressions. In the case of $\nu_{\mu} + e$ (sometimes known as inverse muon or inverse tau decays) one finds

$$\mathcal{M}_{CC} = -\frac{G_{F}}{\sqrt{2}} \bar{\nu}_{\mu} (1 - \gamma^{5}) \nu_{e}.$$  

(10)

| Table I. Values for the $g_{V}$ (vector), $g_{A}$ (axial), $g_{L}$ (left), and $g_{R}$ (right) coupling constants for the known fermion fields. |
|---|---|---|---|
| $e$, $\mu$, $\tau$ | $\nu_{\tau}$ | $\nu_{\mu}$ | $\nu_{e}$ |
| $+\frac{1}{2}$ | $-\frac{1}{2} + \sin^{2} \theta_{W}$ | $+\sin^{2} \theta_{W}$ | $\frac{1}{2} + 2\sin^{2} \theta_{W}$ |
| $u$, $c$, $t$ | $d$, $s$, $b$ | $-\frac{1}{2} + \frac{1}{2} \sin^{2} \theta_{W}$ | $\frac{1}{2} \sin^{2} \theta_{W}$ | $\frac{1}{2} + \frac{1}{2} \sin^{2} \theta_{W}$ |
Here, and in all future cases unless specified, we assume that the four-momentum of the intermediate boson is much smaller than its mass (i.e., \( |q^2| \ll M_{W,Z}^2 \)) such that propagator effects can be ignored. In this approximation, the coupling strength is then dictated primarily by the Fermi constant \( G_F \),

\[
G_F = \frac{g^2}{4\sqrt{2} M_W^2} = 1.1663 \times 10^{-5} \text{ GeV}^{-2}.
\]  

By summing over all polarization and spin states, and integrating over all unobserved momenta, one attains the differential cross section with respect to the fractional energy imparted to the outgoing lepton,

\[
d\sigma_{\nu e} = \frac{2m_e G_F^2 E_\nu}{\pi} \left(1 - \frac{m_e^2 - m_l^2}{2m_e E_\nu}\right),
\]

where \( E_\nu \) is the energy of the incident neutrino and \( m_e \) and \( m_l \) are the masses of the electron and outgoing lepton, respectively. The dimensionless inelasticity parameter \( y \) reflects the kinetic energy of the outgoing lepton, which in this particular example is \( y = \left[E_l - (m_l^2 + m_e^2)/2m_e\right]/E_\nu \). The limits of \( y \) are such that

\[
0 \leq y \leq y_{\text{max}} = 1 - \frac{m_l^2}{2m_e E_\nu + m_e^2}.
\]

Note that in this derivation, we have neglected the contribution from neutrino masses, which in this context is too small to be observed kinematically. The above cross section has a threshold energy imposed by the kinematics of the system, \( E_\nu \geq (m_l^2 + m_e^2)/2m_e \).

In the case where \( E_\nu \gg E_{\text{thresh}} \), integration of the above expression yields a simple expression for the total neutrino cross section as a function of neutrino energy,

\[
\sigma \approx \frac{2m_e G_F^2 E_\nu}{\pi} = \frac{G_F^2 s}{\pi},
\]

where \( s \) is the center-of-mass energy of the collision. Note that the neutrino cross section grows linearly with energy.

Because of the different available spin states, the equivalent expression for the inverse lepton decay of antineutrinos, \( \bar{\nu}_e + e^- \rightarrow \bar{\nu}_l + l^-(1 = \mu \text{ or } \tau) \), has a different dependence on \( y \) than its neutrino counterpart, although the matrix elements are equivalent

\[
\frac{d\sigma_{\bar{\nu} e}}{d\nu} = \frac{2m_e G_F^2 E_{\bar{\nu}}}{\pi} \times \left(1 - \frac{y}{1 - (1 - m_e^2/m_l^2)(1 - y)}\right).
\]

Upon integration, the total antineutrino cross section is approximately a factor of 3 lower than the neutrino cross section. The suppression comes entirely from helicity considerations.

Having just completed a charged current example, we now turn our attention to a pure neutral current exchange, such as witnessed in the reaction

\[
\bar{\nu}_l + e^- \rightarrow \bar{\nu}_l + e^- \quad (1 = \mu \text{ or } \tau).
\]

In the instance of a pure neutral-current interaction, we are no longer at liberty to ignore the left- and right-handed leptonic couplings. As a result, one obtains a more complex expression for the relevant matrix element [for a review, see Adams et al. (2009)]

\[
\mathcal{M}_{\text{NC}} = -\sqrt{2} G_F \left[ g_L \bar{\nu}_l \gamma^\mu (1 - \gamma^5) \nu_l \right]
\]

\[
\quad \times \left[ \bar{\nu}_l \gamma^\mu (1 - \gamma^5) e + g_R \bar{\nu}_l \gamma^\mu (1 + \gamma^5) e \right].
\]

The relation between the coupling constants are dictated by the standard model,

\[
g_L^e = \sqrt{\rho}(1 + \frac{1}{2}), \quad g_R^e = 0,
\]

\[
g_L^\mu = \sqrt{\rho}(l^\mu - Q^e \sin^2 \theta_W), \quad g_R^\mu = \sqrt{\rho}(Q^e \sin^2 \theta_W),
\]

or, equivalently,

\[
g_L^e = \sqrt{\rho}(l^e + l^\mu), \quad g_R^e = \sqrt{\rho}(l^e - l^\mu),
\]

\[
g_L^\mu = g_L^e - g_R^e = \sqrt{\rho}(l^\mu - 2Q^e \sin^2 \theta_W),
\]

\[
g_R^\mu = g_L^e + g_R^e = \sqrt{\rho}(l^\mu).
\]

Here \( l^\mu \) and \( Q^e \) are the weak isospin and electromagnetic charge of the target lepton, \( \rho \) is the relative coupling strength between charged and neutral-current interaction (at tree level, \( \rho = 1 \)), and \( \theta_W \) is the Weinberg mixing angle. The standard model defines a relation between the electroweak couplings and gauge boson masses \( M_W \) and \( M_Z \)

\[
\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}.
\]

In the observable cross section for the neutral-current reactions highlighted above, we find that they are directly sensitive to the left- and right-handed couplings. In the literature, the cross section is often expressed in terms of their vector and axial-vector currents,
Indeed, neutrino direction. A simple kinematic argument shows that it is highly directional in nature. The outgoing electron is emitted at very small angles with respect to the incoming neutrino. This remarkable feature has been exploited extensively in conjunction with the observation of neutral-current deep inelastic scattering (Hasert et al., 1973; Benvenuti et al., 1974), confirmed the existence of weak neutral currents and helped solidify the $SU_2(2) \times U(1)_Y$ structure of the standard model (Weinberg, 1967; t’Hooft, 1971). The very observation of the phenomena made a profound impact on the field of particle physics.

Subsequent experiments further utilized the information from the observed rates of neutral-current reactions as a gauge for measuring $\sin^2 \theta_W$ directly. Neutrino-lepton scattering is a particularly sensitive probe in this regard because to first order (and even to further orders of $\alpha$, see Sec. II.D), the cross sections depend only on one parameter, $\sin^2 \theta_W$.

Various experimental methods have been employed to measure neutrino-lepton scattering. Among the first included the observation of $\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_\mu$ scattering by Reines, Gurr, and Sobel (1976) at the Savannah River Plant reactor complex. Making use of the intense $\bar{\nu}_e$ flux produced in reactors, a $\pm 20\%$ measurement of the weak mixing angle was extracted. A more recent result from the Taiwan EXperiment On Neutrino (TEXANO) experiment (Deniz and Wong, 2008; Deniz et al., 2010) also utilizes reactor antineutrinos as their source. There exists an inherent difficulty in extracting these events, as they are often masked by large low-energy backgrounds, particularly those derived from uranium and thorium decays.

The majority of the recent precision tests have been carried out using high-energy neutrino beams. Experiments such as Gargamelle (Hasert et al., 1973), Brookhaven’s Alternating

\[
g_V = (2g^e_Lg^e_V),
\]

\[
g_A = (2g^e_Lg^A_V),
\]

\[
\frac{d\sigma(\nu_e e \rightarrow \nu_e e)}{dy} = m_\nu G^2_F E_\nu \left((g_V + g_A)^2 + (g_V - g_A)^2 \right)
\]

\[
\times (1 - y)^2 - \frac{m_\nu y}{E_\nu}.
\]

\[
\frac{d\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e)}{dy} = m_\nu G^2_F E_\nu \left((g_V - g_A)^2 + (g_V + g_A)^2 \right)
\]

\[
\times (1 - y)^2 - \frac{m_\nu y}{E_\nu}.
\]

Though we have limited ourselves to discussing neutrino-lepton scattering, the rules governing the coupling strengths are predetermined by the standard model and can be used to describe neutrino-quark interactions as well. A full list of the different possible coupling strengths for the known fermion fields is shown in Table I. A more in-depth discussion of these topics can be found in a variety of introductory textbooks. We highlight the work of Giunti and Kim (2007) as an excellent in-depth resource for the interested reader.

As such, neutrino-electron scattering is a powerful probe of the nature of the weak interaction, both in terms of the total cross section as well as its energy dependence (Marciano and Parsa, 2003). We will briefly examine the experimental tests of these reactions in the next section.

Before leaving neutrino-lepton interactions completely, we turn our attention to the last possible reaction archetype, where the charged current and neutral-current amplitudes interfere with one another. Such a combined exchange is realized in $\nu_e + e^- \rightarrow \nu_e + e^- \text{ scattering}$ (see Fig. 3). The interference term comes into play by shifting $g^e_V \rightarrow g^e_V + \frac{1}{2}$ and $g^A_V \rightarrow g^A_V + \frac{1}{2}$.

One remarkable feature of neutrino-electron scattering is that it is highly directional in nature. The outgoing electron is emitted at very small angles with respect to the incoming neutrino direction. A simple kinematic argument shows that indeed

\[
E_\nu \theta^2 \leq 2m_e.
\]

This remarkable feature has been exploited extensively in various neutrino experiments, particularly for solar neutrino detection. The Kamiokande neutrino experiment was the first to use this reaction to reconstruct $^6$He neutrino events from the Sun and point back to the source. The Super-Kamiokande experiment later expanded the technique, creating a photograph of the Sun using neutrinos (Fukuda et al., 1998). The technique was later used by other solar experiments, such as the Sudbury Neutrino Observatory (SNO) (Ahmad et al., 2001, 2002a, 2002b) and Borexino (Alimonti et al., 2002; Arpesella et al., 2008).

C. Experimental tests of electroweak theory

Neutrino-lepton interactions have played a pivotal role in our understanding of the working of the electroweak force and the standard model as a whole. Consider as an example the first observation of the reaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ made with the CERN bubble chamber neutrino experiment, Gargamelle (Hasert et al., 1973); see Fig. 4. This observation, in conjunction with the observation of neutral-current deep inelastic scattering (Hasert et al., 1973; Benvenuti et al., 1974), confirmed the existence of weak neutral currents and helped solidify the $SU_2(2) \times U(1)_Y$ structure of the standard model (Weinberg, 1967; t’Hooft, 1971). The very observation of the phenomena made a profound impact on the field of particle physics.

Subsequent experiments further utilized the information from the observed rates of neutral-current reactions as a gauge for measuring $\sin^2 \theta_W$ directly. Neutrino-lepton scattering is a particularly sensitive probe in this regard because to first order (and even to further orders of $\alpha$, see Sec. II.D), the cross sections depend only on one parameter, $\sin^2 \theta_W$.

Various experimental methods have been employed to measure neutrino-lepton scattering. Among the first included the observation of $\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_\mu$ scattering by Reines, Gurr, and Sobel (1976) at the Savannah River Plant reactor complex. Making use of the intense $\bar{\nu}_e$ flux produced in reactors, a $\pm 20\%$ measurement of the weak mixing angle was extracted. A more recent result from the Taiwan EXperiment On Neutrino (TEXANO) experiment (Deniz and Wong, 2008; Deniz et al., 2010) also utilizes reactor antineutrinos as their source. There exists an inherent difficulty in extracting these events, as they are often masked by large low-energy backgrounds, particularly those derived from uranium and thorium decays.

The majority of the recent precision tests have been carried out using high-energy neutrino beams. Experiments such as Gargamelle (Hasert et al., 1973), Brookhaven’s Alternating

\[
E_\nu \theta^2 \leq 2m_e.
\]

\[
\frac{d\sigma(\nu_e e \rightarrow \nu_e e)}{dy} = m_\nu G^2_F E_\nu \left((g_V + g_A)^2 + (g_V - g_A)^2 \right)
\]

\[
\times (1 - y)^2 - \frac{m_\nu y}{E_\nu}.
\]

\[
\frac{d\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e)}{dy} = m_\nu G^2_F E_\nu \left((g_V - g_A)^2 + (g_V + g_A)^2 \right)
\]

\[
\times (1 - y)^2 - \frac{m_\nu y}{E_\nu}.
\]

The fact that such a picture was taken underground during both day and night is also quite remarkable.

FIG. 4 (color online). The first candidate leptonic neutral-current event from the Gargamelle CERN experiment. An incoming muon-antineutrino knocks an electron forwards (towards the left), creating a characteristic electronic shower with electronpositron pairs. Photograph from CERN.
Gradient Synchrotron (AGS) source (Ahrens et al., 1983, 1990; Abe et al., 1989), CERN HAMburg Rome Moscow (CHARM-II) (Vilain et al., 1995a, 1995b), Chicago-Columbia-Fermilab-Rochester (CCFR) (Mishra et al., 1990), and NuTeV (Formaggio et al., 2001) fall within this category. Often these experiments exploit the rise in cross section with energy to increase the sample size collected for analysis. Stopped pion beams have also been used for these reactions across the various energy scales. The first step in our journey involves thresholdless interactions, which can be initiated when the neutrino has essentially zero momentum. Such processes include coherent scattering and neutrino capture.²

### Table II. The integrated cross section for neutrino-lepton scattering interactions. Corrections due to leptonic masses and radiative QED corrections are ignored. Cross sections are compared to the asymptotic cross section \( \sigma_0 = G_F^2 s / \pi \). Listed are the experiments which have measured the given reaction, including Gargamelle (Hasert et al., 1973), the Savannah River Plant (Reines, Gurr, and Sobel, 1976), Brookhaven National Laboratory (BNL) (Ahrens et al., 1983; Abe et al., 1989; Ahrens et al., 1990), LAMPF (Allen et al., 1993), LSND (Auerbach et al., 2001), CCFR (Mishra et al., 1990), CHARM (Vilain et al., 1995a; Vilain et al., 1995b), NuTeV (Formaggio et al., 2001), and TEXONO (Deniz and Wong, 2008).

| Reaction | Type | \( \sigma(E_r) \gg \sigma_0 \) | Experimental probes |
|----------|------|-------------------------------|-------------------|
| \( \bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \) | CC and NC | \( \frac{1}{4} \sin^2 \theta_W + \frac{1}{8} \sin^4 \theta_W \) | CHARM, LAMPF, LSND |
| \( \bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \) | CC and NC | \( \frac{1}{12} + \frac{1}{3} \sin^2 \theta_W + \frac{1}{3} \sin^4 \theta_W \) | CHARM, TEXONO, Savannah River |
| \( \bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^- \) | CC | \( \frac{1}{4} \) | |
| \( \nu_\mu e^- \rightarrow \nu_\mu e^- \) | CC | \( \frac{1}{12} - \frac{1}{2} \sin^2 \theta_W + \frac{1}{4} \sin^4 \theta_W \) | CHARM, CCFR, NuTeV |
| \( \nu_\mu e^- \rightarrow \nu_\mu e^- \) | NC | \( \frac{1}{4} \) | |
| \( \nu_\mu e^- \rightarrow \nu_\mu e^- \) | NC | \( \frac{1}{12} - \frac{1}{2} \sin^2 \theta_W + \frac{1}{4} \sin^4 \theta_W \) | Gargamelle, BNL |

D. Radiative corrections and \( G_F \)

Upon inspection of the cross section formalisms discussed above, it is clear that, with the exception of ratios, one is critically dependent on certain fundamental constants, such as the size of the weak coupling constant \( G_F \). Ideally, one wants to separate the dependence on the weak mixing angle from the Fermi constant strength. Fortunately, measurements of the muon lifetime provide such a possibility, as it is inversely proportional to the coupling strength \( G_F \) and the muon mass \( m_\mu \).

\[
(\tau_\mu)^{-1} = \frac{G_F^2 m_\mu^5}{192 \pi^3} f(\rho) \left( 1 + \frac{3}{5} \frac{m_\mu^2}{M_W^2} \right) [1 + \Delta(\alpha)].
\]  

(22)

In the above expression, \( f(\rho) \) is a phase factor, the \( m_\mu^2/M_W^2 \) factor encapsulates the W-boson propagator, and \( \Delta(\alpha) \) encodes the QED radiative field corrections. For completeness, we list these correction factors:

\[
f(\rho) = 1 - 8 \rho + 8 \rho^3 - \rho^4 - 12 \rho^2 \ln \rho \approx 0.999813,
\]

(23)

\[
\Delta = \alpha \left( \frac{25 \pi^2}{8} - \frac{\pi^2}{2} - 9 + 4 \pi^2 + 12 \ln \rho \right) \rho
\]

\[+ 16 \pi^2 \rho^{3/2} + O(\rho^2) + O(\alpha^2) + \ldots, \tag{24}\]

where \( \rho = (m_e/m_\mu)^2 \) and \( \alpha \) is the fine structure constant. Radiative QED corrections have been calculated to second order and higher in electroweak theory paving the way to precision electroweak tests of the standard model. The best measurement of the muon lifetime to date has been made by the MuLan experiment (Webber et al., 2011), yielding a value for \( G_F \) of 1.166 378 (8)(7) \times 10^{-5} \text{ GeV}^{-2} \), a precision of 0.6 ppm.

At tree level, knowing \( G_F \) (and \( \alpha \) and \( M_Z \) it is possible to exactly predict the value of \( \sin^2 \theta_W \) and test this prediction against the relevant cross section measurements. However, once one introduces one-loop radiative contributions, dependencies on the top and Higgs masses are also introduced. The size of these corrections depends partially on the choice of the normalization scheme. The two commonly used renormalization schemes include the Sirlin on-shell model (Sirlin, 1980) and the modified minimal subtraction scheme (Marciano and Sirlin, 1981). In the latter method, the Weinberg angle is defined by \( M_W \) and \( M_Z \) at some arbitrary renormalized mass scale \( \mu \), which is typically set to the electroweak scale \( M_Z \):

\[
\sin^2 \theta^\text{WS} = 1 - \frac{M_W^2(\mu)^2}{M_Z^2(\mu)^2}.
\]

(25)

Such radiative corrections, although small, often need to be accounted for in order to properly predict the \( \sin^2 \theta_W \) value. Theoretical compilation of such radiative effects can be found in a variety of papers [see, for example, Marciano and Parsa (2003)].

III. THRESHOLDLESS PROCESSES: \( E_r \sim 0-1 \text{ MeV} \)

Having established the formalism of basic neutrino interactions, we turn our attention toward describing neutrino interactions across the various energy scales. The first step in our journey involves thresholdless interactions, which can be initiated when the neutrino has essentially zero momentum. Such processes include coherent scattering and neutrino capture.²

A. Coherent scattering

Coherent scattering involves the neutral-current exchange where a neutrino interacts \emph{coherently} with the nucleus.

²Technically, neutrino elastic scattering off of free electrons also falls within this definition, as discussed earlier in this paper.
\[ \nu + A_N^Z \rightarrow \nu + A_N^{Z+1} \]  

(26)

Shortly after the discovery of neutral-current neutrino reactions, Freedman, Schramm, and Tubbs pointed out that neutrino-nucleus interactions should also exist (Freedman, Schramm, and Tubbs, 1977). Furthermore, one could take advantage of the fact that at low energies the cross section should be coherent across all of the nucleons present in the nucleus. As a result, the cross section grows as the square of the atomic number \( A^2 \). Such an enhancement is possible if the momentum transfer of the reaction is much smaller than the inverse of the target size. Letting \( Q \) represent the momentum transfer and \( R \) the nuclear radius, the coherence condition is satisfied when \( QR \ll 1 \). Under these conditions, the relevant phases have little effect, allowing the scaling to grow as \( A^2 \).

Given a recoil kinetic energy \( T \) and an incoming neutrino energy \( E_\nu \), the differential cross section can be written compactly as the following:

\[ \frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left( 1 - \frac{M_A T}{2E_\nu} \right) F(Q^2), \]  

(27)

where \( M_A \) is the target mass (\( M_A = AM_{\text{nucleon}} \)), \( F(Q^2) \) is the nucleon form factor, and \( Q_W \) is the weak current term

\[ Q_W = N - Z(1 - 4\sin^2\theta_W). \]  

(28)

The cross section essentially scales quadratically with neutron (\( N \)) and proton (\( Z \)) number; the latter highly suppressed due to the \( 1 - 4\sin^2\theta_W \approx 0 \) term. The form factor \( F(Q^2) \) encodes the coherence across the nucleus and drops quickly to zero as \( QR \) becomes large.

Despite the strong coherent enhancement enjoyed by this process, this particular interaction has yet to be detected experimentally. Part of the obstacle stems from the extremely small energies of the emitted recoil. The maximum recoil energy from such an interaction is limited by the kinematics of the elastic collision,

\[ T_{\text{max}} = \frac{E_\nu}{1 + M_A/2E_\nu}, \]  

(29)

similar to that of any elastic scatter where the mass of the incoming particle is negligible. Several experiments have been proposed to detect this interaction, often taking advantage of advances in recoil detection typically utilized by dark matter experiments (Scholberg, 2006; Formaggio, Figueroa-Feliciano, and Anderson, 2012). The interaction has also been proposed as a possible mechanism for cosmic relic neutrinos, due to its nonzero cross section at zero momentum. However, the \( G_F^2 \) suppression makes detection beyond the reach of any realizable experiment.

**B. Neutrino capture on radioactive nuclei**

Neutrino capture on radioactive nuclei, sometimes referred to as enhanced or stimulated beta decay emission, constitutes another thresholdless mechanism in our library of possible neutrino interactions. The process is similar to that of ordinary beta decay

\[ A_N^Z \rightarrow A_N^{Z+1} + e^- + \bar{\nu}_e, \]  

(30)

except the neutrino is interacting with the target nucleus

\[ \nu_\alpha + A_N^Z \rightarrow e^- + A_{N-1}^{Z+1}. \]  

(31)

This reaction has the same observable final states as its beta decay counterpart. What sets this reaction apart from other neutrino interactions is that the process is exothermic and hence no energy is required to initiate the reaction. The cross section amplitude is directly related to that of beta decay. Using the formalism of Beacom and Vogel (1999), the cross section can be written as

\[ \frac{d\sigma}{d\cos\theta} = \frac{G_F^2|V_{ud}|^2 F(Z_f, E_e)}{2\pi\beta_e} \left[ (1 + \beta_e\beta_e\cos\theta) \right. \]

\[ + \left. 3\lambda^2 \left( 1 - \frac{1}{3}\beta_e\beta_e\cos\theta \right) \right]. \]  

(32)

where \( \beta_e \) and \( \beta_e \) are the electron and neutrino velocities, respectively, \( E_e, p_e, \) and \( \cos\theta \) are the electron energy, momentum, and scattering angle, \( \lambda^2 \) is the axial-to-vector coupling ratio, and \( |V_{ud}|^2 \) is the Cabbibo angle. The Fermi function \( F(Z_f, E) \) encapsulates the effects of the Coulomb interaction for a given lepton energy \( E_e \) and final-state proton number \( Z_f \). We discuss the coupling strengths \( f_V(0) \) and \( \lambda^2 \) later.

In Eq. (32), we no longer assume that \( \beta_e \rightarrow c. \) If the neutrino flux is proportional to the neutrino velocity, then the product of the cross section and the flux results in a finite number of observable events. If the neutrino and the nucleus each possess negligible energy and momentum, the final-state electron is ejected as a monoenergetic particle whose energy is above the end-point energy of the reaction.

The interaction cross section of very low-energy neutrinos was first suggested by Weinberg (1962). Recently, this process has attracted particular interest thanks to the work by Coco, Mangano, and Messina (2007), where they considered the process as a means to detect cosmological neutrinos. The reaction has received attention partially due to the advancement of beta decay experiments in extending the reach on neutrino mass scales. The mechanism, like its coherent counterpart, remains to be observed.

**IV. LOW-ENERGY NUCLEAR PROCESSES:**

\( E_\nu \sim 1-100 \text{ MeV} \)

As the energy of the neutrino increases, it is possible to probe the target nucleus at smaller and smaller length scales. Whereas coherent scattering only allows one to “see” the nucleus as a single coherent structure, higher energies allow one to access nucleons individually. These low-energy interactions have the same fundamental characteristics as those of lepton scattering, though the manner in which they are gauged and calibrated is very different. And, unlike the thresholdless scattering mechanisms discussed previously, these low-energy nuclear processes have been studied extensively in neutrino experiments.

---

3In principle, any elastic interaction on a free target has a finite cross section at zero momentum, but such interactions would be impossible to discern due to the extremely small transfer of momentum.
A. Inverse beta decay

The simplest nuclear interaction that we can study is antineutrino-proton scattering, otherwise known as inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$  
(33)

Inverse beta decay represents one of the earliest reactions to be studied, both theoretically (Bethe and Peierls, 1934) and experimentally (Reines, Gurr, and Sobel, 1976). This reaction is typically measured using neutrinos produced from fission in nuclear reactors. The typical neutrino energies used to probe this process range from threshold\(^4\) \(E_v \gtrsim 1.806 \text{ MeV}\) to about \(10 \text{ MeV}\). As this reaction plays an important role in understanding supernova explosion mechanisms, its relevance at slightly higher energies \((10–20 \text{ MeV})\) is also of importance. In this paper, we follow the formalism of Beacon and Vogel (1999), who expand the cross section on the proton to first order in nucleon mass in order to study the cross section’s angular dependence. In this approximation, all relevant form factors approach their zero-momentum limit.

The relevant matrix element is given by

$$\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} \left( \langle \bar{\nu}_e | j^\mu j^\nu | e \rangle - \gamma_\mu \gamma^\nu f_A(0) \right) - \frac{i f_p(0)}{2M_n} \sigma_{\mu\nu} q^\nu \langle \bar{\nu}_e | \gamma^\nu (1 - \gamma^5) | e \rangle.$$  
(34)

In the above equation, \(f_V, f_A, \) and \(f_p\) are nuclear vector, axial vector, and Pauli (weak magnetism) form factors evaluated at zero-momentum transfer (for greater detail on the form factor behavior, see Sec. IV.D). To first order, the differential cross section can therefore be written as

$$\frac{d\sigma(\bar{\nu}_e p \rightarrow e^+ n)}{d\cos \theta} = G_F^2 |V_{ud}|^2 E_e p_e \frac{1}{2\pi} \left[ f_V^2(0)(1 + \beta_e \cos \theta) + 3f_A^2(0)(1 - \beta_e \cos \theta) \right].$$  
(35)

where \(E_e, p_e, \beta_e, \) and \(\cos \theta\) refer to the electron’s energy, momentum, velocity, and scattering angle, respectively.

A few properties in Eq. (35) immediately attract our attention. First and foremost is that the cross section neatly divides into two distinct “components”: a vectorlike component, called the Fermi transition, and an axial-vectorlike component, referred to as Gamow-Teller. We talk more about Fermi and Gamow-Teller transitions later.

A second striking feature is its angular dependence. The vector portion has a clear \(1 + \beta_e \cos \theta\) dependence, while the axial portion has a \(1 - (\beta_e/3) \cos \theta\) behavior, at least to first order in the nucleon mass. The overall angular effect is weakly backward scattered for antineutrino-proton interactions, showing that the vector and axial-vector terms both contribute at equivalent amplitudes. This is less so for cases where the interaction is almost purely Gamow-Teller in nature, such as \(\nu d\) reactions. In such reactions, the backwards direction is more prominent. Such angular distributions have been posited as an experimental tag for supernova detection (Beacom, Farr, and Vogel, 2002).

The final aspect of the cross section that is worthy to note is that it has a near one-to-one correspondence with the beta decay of the neutron. We explore this property in greater detail in the next section.

B. Beta decay and its role in cross section calibration

The weak interaction governs both the processes of decay and scattering amplitudes. It goes to show that, especially for simple systems, the two are intimately intertwined, often allowing one process to provide robust predictions for the other. The most obvious nuclear target where this takes place is in the beta decay of the neutron. In much the same way as muon decay provided a calibration of the Fermi coupling constant for purely leptonic interactions (Sec. II.D), neutron beta decay allows one to make a prediction of the inverse beta decay cross section from experimental considerations alone.

For the case of neutron beta decay, the double differential decay width at tree level is given by (Nico and Snow, 2005)

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_v} = G_F^2 |V_{ud}|^2 (1 + 3\lambda^2)^2 \left[ \langle \bar{\nu}_e | T_e + m_e \rangle \right] \times \left( E_0 - T_e \right)^2 \left[ 1 + A \frac{\bar{\nu}_e \cdot \tilde{p}_e}{T_e E_v} + \frac{m_e}{T_e} \right] \times \left( B \frac{\bar{\nu}_e \cdot \tilde{p}_e}{T_e E_v} + D \frac{\bar{\nu}_e \cdot \tilde{p}_e}{T_e E_v} \right).$$

---

\(\text{Table III. Neutron decay parameters contributing to Eq. (36). Values extracted from Nico and Snow (2005) and Nakamura, K. \textit{et al.} (2010).}

| Constant | Expression | Numerical value | Comment |
|----------|------------|----------------|---------|
| \(A\) | \(\frac{|V_{ud}|^2}{1 - |V_{ud}|^2}\) | \(-1.2694 \pm 0.0028\) | Axial and vector coupling ratio |
| \(a\) | \(\frac{2|\lambda|^4}{1 + |\lambda|^2}\) | \(-0.103 \pm 0.004\) | Electron-antineutrino asymmetry |
| \(b\) | \(0\) | \(0\) | Fierz interference |
| \(A\) | \(-2\frac{|\lambda|^2 - |\lambda|^4 \cos \theta}{1 + 3|\lambda|^2}\) | \(-0.1173 \pm 0.0013\) | Spin-electron asymmetry |
| \(B\) | \(+2\frac{|\lambda|^2 - |\lambda|^4 \cos \theta}{1 + 3|\lambda|^2}\) | \(0.9807 \pm 0.0030\) | Spin-antineutrino asymmetry |
| \(D\) | \(\sqrt{\frac{M_n}{2\lambda}} \cos \theta\) | \((-4.6 \times 10^{-4}\) | T-odd triple product |
| \(f(1 + \delta_R)\) | \([\frac{m_e}{\lambda^2}] f_R G_F^2 |V_{ud}|^2 (1 + 3\lambda^2)^{-1}\) | \(1.71480 \pm 0.000002\) | Theoretical phase space factor |
| \(\tau_n\) | \([\frac{m^2}{\lambda^2}] f_R G_F^2 |V_{ud}|^2 (1 + 3\lambda^2)^{-1}\) | \((858.7 \pm 0.8)\) s | Neutron lifetime |

---

\(^4\)The neutrino energy threshold \(E_v^{\text{thresh}}\) in the laboratory frame is defined by \([(m_n + m_e)^2 - m_p^2]/2m_p\).
Here $\hat{p}_e$ and $\hat{p}_x$ are the electron and neutrino momenta, $T_x$ is the electron’s kinetic energy, $E_x$ is the outgoing antineutrino energy, $E_0$ is the end-point energy for beta decay, and $\sigma_x$ is the neutron spin. The definitions of the other various constants are listed in Table III.

Integrating over the allowed phase space provides a direct measure of the energy-independent portion of the inverse beta decay cross section, including internal radiative corrections. That is, Eq. (35) can also be written as

$$\frac{d\sigma(\hat{p}_e p \rightarrow e^+ n)}{d\cos\theta} = \frac{2\pi^2}{2m_e^2 f(1 + \delta_R)^2} \frac{E_x p_x}{E_0} \left[ (1 + \beta_x \cos\theta) + 3\lambda^2 \left(1 - \frac{\beta_x}{3} \cos\theta\right) \right].$$

The term $f(1 + \delta_R)$ is a phase space factor that includes several inner radiative corrections. Additional radiative corrections and effects due to finite momentum transfer have been evaluated. From a theoretical standpoint, therefore, the inverse beta decay cross section is well predicted, with uncertainties around $\pm 0.5\%$.

The ability for measured beta decay rates to assist in the evaluation of neutrino cross sections is not limited solely to inverse beta decay. Beta decay transitions also play a pivotal role in the evaluation of neutrino cross sections for a variety of other target nuclei. Nuclei which relate back to superallowed nuclear transitions stand as one excellent example. Isotopes that undergo superallowed Fermi transitions ($0^+ \rightarrow 0^+$) provide the best test of the conserved vector current (CVC) hypothesis (Gerstein and Zeldovich, 1956; Feynman and Gell-Mann, 1958) and, if one includes measurements of the muon lifetime, the most accurate measurements of the quark mixing matrix element of the Cabibbo-Kobayashi-Maskawa matrix $V_{ud}$ (Hardy and Towner, 1999). Typically, the value for $V_{ud}$ can be extracted by looking at the combination of the statistical rate function ($F$) and the partial half-life ($t$) of a given superallowed transition. Because the axial current cannot contribute in lowest order to transitions between spin-0 states, the experimental $Ft$ value is related directly to the vector coupling constant. For an isospin-1 multiplet, one obtains

$$|V_{ud}|^2 = \frac{K}{2G^2_F(1 + \Delta_R)Ft},$$

where $\Delta_R$ are the nucleus-independent radiative corrections in $0^+ \rightarrow 0^+$ transitions and $K$ is defined as $K = 2\pi^3 \ln 2/m_e^2 = (8120.27\pm0.01) \times 10^{-10}$ GeV$^{-4}$ s. The $Ft$ value from various transitions are very precisely measured (down to the 0.1% level) to be $3072.3\pm2.0$, while the radiative corrections enter at the 2.4% level (Towner, 1998). The process is not directly relatable to that of inverse beta decay because of the lack of the axial form factor, but it provides a strong constraint on the validity of the CVC hypothesis.

Even excluding neutron decay and superallowed transitions, beta decay measurements also play an important role in the calculation of low-energy cross sections simply because they represent a readily measurable analog to their neutrino interaction counterpart. For example, the $\beta^+$ decay from $^{12}\text{N}$ to the ground state of $^{12}\text{C}$ is often used to calibrate calculations of the exclusive cross section of $^{12}\text{C}(\nu_x, e^-)^{12}\text{N}$ (Fukugita, Kohyama, and Kubodera, 1988). In the case of deuterium targets, the decay width of tritium beta decay provides an extremely strong constraint on the $\nu d$ cross section (Nakamura et al., 2001). Finally, though not least, both allowed and forbidden $\beta^\pm$ decays often allow a direct measure of the Gamow-Teller contribution to the total cross section. Comparisons of neutrino reactions on $^{37}\text{Cl}$ and the decay process $^{37}\text{Ca}(\beta^+)^{37}\text{K}$ are prime example of this last constraint technique (Außerhofer et al., 1994).

C. Theoretical calculations of neutrino-deuteron cross sections

Next to hydrogen, no nuclear target is better understood than deuterium. Neutrino-deuteron scattering plays an important role in experimental physics, as heavy water ($\text{D}_2\text{O}$) was the primary target of SNO (Ahmad et al., 2001, 2002a, 2002b, 2004; Aharmin et al., 2005, 2007, 2008). The SNO experiment is able to simultaneously measure the electron and nonelectron component of the solar neutrino spectrum by comparing the charged current and neutral-current neutrino reactions on deuterium

$$\nu_e + d \rightarrow e^- + p + p \quad \text{(charged current)},$$

$$\nu_x + d \rightarrow \nu_x + n + p \quad \text{(neutral current)}.$$

Results from the experiment allowed confirmation of the flavor-changing signature of neutrino oscillations and verification of the Mikheyev-Smirnov-Wolfenstein mechanism (Wolfenstein, 1978; Mikheyev and Smirnov, 1989).

Deuterium with its extremely small binding energy ($E_{\text{bind}}\approx2.2$ MeV) has no bound final state after scattering. There exist two prominent methods for calculating such cross sections. The first method, sometimes referred to in the literature as the elementary-particle treatment (EPT) or at times the standard nuclear physics approach, was first introduced by Fujii and Yamaguchi (1964) and Kim and Primakoff (1965). The technique treats the relevant nuclei as fundamental particles with assigned quantum numbers. A transition matrix element for a given process is parameterized in terms of the nuclear form factors solely based on the transformation properties of the nuclear states, which in turn are constrained from experimental data. Such a technique provides a robust method for calculating $\nu d$ scattering. Typically one divides the problem into two parts; the one-body impulse approximation terms and two-body exchange currents acting on the appropriate nuclear wave functions. In general, the calculation of these two-body currents presents the most difficulty in terms of verification. However, data gathered from $n + p \rightarrow d + \gamma$ scattering provide one means of constraining any terms which may arise in $\nu d$ scattering. An additional means of verification, as discussed previously, involves the reproduction of the experimental tritium beta decay width, which is very precisely measured.

An alternative approach to such calculations has recently emerged on the theoretical scene based on effective field theory (EFT) which has proven to be particularly powerful...
in the calculations of $\nu d$ scattering (Butler and Chen, 2000; Butler, Chen, and Kong, 2001). EFT techniques make use of the gap between the long-wavelength and short-range properties of nuclear interactions. Calculations separate the long-wavelength behavior of the interaction, which can be readily calculated, while absorbing the omitted degrees of freedom into effective operators which are expanded in powers of some cutoff momentum. Such effective operators can then be related directly to some observable or constraint that fixes the expansion. In the case of $\nu d$ scattering, the expansion is often carried out as an expansion of the pion mass $q/m_\pi$. EFT separates the two-body current process such that it is dependent on one single parameter, referred to in the literature as $L_{1A}$. This low-energy constant can be experimentally constrained, and in doing so provides an overall regularization for the entire cross section. Comparisons between these two different methods agree to within 1%–2% for energies relevant for solar neutrinos ($<20$ MeV) (Nakamura et al., 2001; Mosconi, Ricci, and Truhlik, 2006; Mosconi et al., 2007). In general, the EFT approach has been extremely successful in providing a solid prediction of the deuterium cross section, and central to the reduction in the theoretical uncertainties associated with the reaction (Adelberger et al., 2010). Given the precision of such cross sections, one must often include radiative corrections (Towner, 1998; Beacom and Parke, 2001; Kurylov, Ramsey-Musolf, and Vogel, 2002).

D. Other nuclear targets

So far we have only discussed the most simple of reactions; that is, scattering of antineutrinos off of free protons and scattering of neutrinos off of deuterium, both of which do not readily involve any bound states. In such circumstances, the uncertainties involved are small and well understood. But what happens when we expand our arsenal and attempt to evaluate more complex nuclei or nuclei at higher momenta transfer? The specific technique used depends in part on the type of problem that one is attempting to solve, but it usually falls in one of three main categories:

1. For the very lowest energies, one must consider the exclusive scattering to particular nuclear bound states and provide an appropriate description of the nuclear response and correlations among nucleons. The shell model is often invoked here, given its success in describing Fermi and Gamow-Teller amplitudes (Caurier et al., 2005).

2. At higher energies, enumeration of all states becomes difficult and cumbersome. However, at this stage one can begin to look at the collective excitation of the nucleus. Several theoretical tools, such as the random phase approximation (RPA) (Auerbach and Klein, 1983) and extensions of the theory, including continuous random phase approximation (CRPA) (Kolbe, Langanke, and Vogel, 1999), and quasiparticle random phase approximation (QRPA) (Volpe et al., 2000), have been developed along this strategy.

3. Beyond a certain energy scale, it is possible to begin describing the nucleus in terms of individual, quasifree nucleons. Techniques in this regime are discussed later in the text.

We first turn our attention to the nature of the matrix elements which describe the cross section amplitudes of the reaction under study. In almost all cases, we wish to determine the amplitude of the matrix element that allows us to transition from some initial state $i$ (with initial spin $J_i$) to some final state $f$ (with final spin $J_f$). For a charged current interaction of the type $\nu_e + A^Z_{N-1} \rightarrow e^- + A^Z_{N-1} + \nu_e$, the cross section can be written in terms of a very general expression

$$
\frac{d\sigma}{d\cos\theta} = \frac{E_e p_e}{2\pi} \sum_j \frac{1}{(2J_i + 1)} \left| \sum_{M_i, M_f} \langle f | H_W | i \rangle \right|^2,
$$

where $E_e$, $p_e$, and $\cos\theta$ are the outgoing electron energy, momentum, and scattering angle, respectively, and $J_i$ is the total spin of the target nucleus. The sum is carried over all the accessible spins of the initial and final states. The term in brackets encapsulates the elements due to the hadronic-lepton interaction. A Fourier transform of the above expression allows one to express the matrix elements of the Hamiltonian in terms of the four-momenta of the initial and final states of the reaction. The Hamiltonian which governs the strength of the interaction is given by the product of the hadronic current $H(\vec{x})$ and the leptonic current $J(\vec{x})$

$$
H^{CC}_W = \frac{G_F V_{ud}}{\sqrt{2}} \int [j^{CC, \mu}(\vec{x})H^{CC}_\mu(\vec{x}) + \text{H.c.}]d\vec{x},
$$

$$
H^{NC}_W = \frac{G_F}{\sqrt{2}} \int [j^{NC, \mu}(\vec{x})H^{NC}_\mu(\vec{x}) + \text{H.c.}]d\vec{x},
$$

where

$$
H^{CC}_\mu(\vec{x}) = V^{\pm}_\mu(\vec{x}) + A^{\pm}_\mu(\vec{x}),
$$

$$
H^{NC}_\mu(\vec{x}) = (1 - 2\sin^2 \theta_W)V^{\nu}_\mu(\vec{x}) + A^{\nu}_\mu(\vec{x}) - 2\sin^2 \theta_W V^{\nu}_\mu.
$$

We concentrate on the charged current reaction first. In the above expression, the $V^{\pm}$ and $A^{\pm}$ components denote the vector and axial-vector currents, respectively. The ± and 0 index notation denotes the three components of the isospin raising (lowering) currents for the neutrino (or antineutrino) reaction. The final ingredient $V^{\nu}$ denotes the isoscalar current. For the case of the impulse approximation, it is possible to write down a general representation of the hadronic weak current in terms of the relevant spin contributions

$$
\langle f | V^{\nu} (q^2) | i \rangle = \tilde{u}(p') \frac{\tau^a}{2} \left[ F_1(q^2) \gamma_\mu + i \frac{F_2(q^2)}{2m} \sigma_{\mu\nu} q^\nu \right. \\
\left. + \frac{q_\mu}{M_N} F_3(q^2) \right] u(p),
$$

$$
\langle f | A^{\nu} (q^2) | i \rangle = \tilde{u}(p') \frac{\tau^a}{2} \left[ F_A(q^2) \gamma_\mu \gamma_5 + \frac{F_P}{M_N} (q^2) \gamma_\mu \gamma_5 \right. \\
\left. + \frac{F_T}{M_N} (q^2) \sigma_{\mu\nu} q^\nu \gamma_5 \right] u(p).
$$

Here $\tau^a$ is indexed as $a = \pm, 0$, $\sigma_{\mu\nu}$ are the spin matrices, $\tilde{u}(p')$ and $u(p)$ are the Dirac spinors for the target and final-state nucleon, $M_N$ is the (averaged) nucleon mass, and $F_{[S,1,A,2,F,T]}(q^2)$ correspond to the scalar, Dirac, axial vector, Pauli, pseudoscalar, and tensor weak form factors, respectively. The invariance of the strong interaction under isospin simplifies the picture for the charged current interaction, as both the scalar and tensor components are zero.
In order to proceed further, one needs to make some link between the form factors probed by weak interactions and those from pure electromagnetic interactions. Fortunately, the CVC hypothesis allows us to do just that:

$$F_1(q^2) = F_1^N(q^2) - F_1^p(q^2).$$

$$F_2(q^2) = F_2^N(q^2) - F_2^p(q^2).$$

Here $F_1^p$ and $F_2^p$ are known in the literature as the electromagnetic Dirac and Pauli form factors of the proton and neutron, respectively. In the limit of zero-momentum transfer, the Dirac form factors reduce to the charge of the nucleon, while the Pauli form factors reduce to the nucleon’s magnetic moments

$$F_1^N(0) = q_N = \begin{cases} 1 & \text{if proton,} \\ 0 & \text{if neutron} \end{cases}$$

$$F_2^N(0) = \begin{cases} \frac{\mu_p}{\mu_N} - 1 & \text{if proton,} \\ \frac{\mu_n}{\mu_N} & \text{if neutron.} \end{cases}$$

Here $q_N$ is the nucleon charge, $\mu_N$ is the nuclear magneton, and $\mu_{p,n}$ are the proton and neutron magnetic form factors.

To ascertain the $q^2$ dependence of these form factors, it is common to use the Sachs electric and magnetic form factors and relate them back to $F_1^p$ and $F_2^p$,

$$G_1^N(q^2) = F_1^N(q^2) - \eta F_2^N(q^2),$$

$$G_2^N(q^2) = F_2^N(q^2) + \eta F_1^N(q^2),$$

with $\eta = -q^2/4M_N$ and

$$G_1^p(q^2) = G_D(q^2),$$

$$G_2^p(q^2) = G_M(q^2),$$

$$G_1^N(q^2) = \frac{\mu_p}{\mu_N} G_D(q^2),$$

$$G_2^N(q^2) = \frac{\mu_n}{\mu_N} G_M(q^2).$$

Here $G_D(q^2)$ is a dipole function determined by the charge radius of the nucleon. Empirically, the dipole term can be written as

$$G_D(q^2) = \left(1 - \frac{q^2}{m_N^2}\right)^{-1},$$

where $m_N = 0.84$ MeV.

We now turn our attention to the axial portion of the current, where the terms $F_A(q^2)$ and $F_P(q^2)$ play a role. For $F_A(q^2)$, one also assumes a dipole-like behavior, but with a different coupling and axial mass term ($m_A$)

$$F_A(q^2) = -g_A G_A(q^2),$$

$$G_A(q^2) = \left(1 - \frac{q^2}{m_A^2}\right)^{-1}. \quad (42)$$

The Goldberger-Treiman relation allows one to also relate the pseudoscalar contribution in terms of the axial term as well; typically

$$F_P(q^2) = \frac{2m_A^2}{m_N^2 - q^2} F_A(q^2),$$

where $m_\pi$ is the pion mass. In the limit that the momentum exchange is small (such as in neutron decay or inverse beta decay), the form factors reduce to the constants defined previously in this section

$$f_V(0) = F_1(0) = 1,$$

$$f_P(0) = F_2(0) = \frac{\mu_p - \mu_n}{\mu_N} - 1 \approx 3.706,$$

$$f_A(0) = F_A(0) = -g_A,$$

with $\lambda = f_A(0)/f_V(0) = -1.2694 \pm 0.0028$, as before (Nakamura, K. et al., 2010).

The above represents an approach that works quite well when the final states are simple, for example, when one is dealing with a few-nucleon system with no strong bound states or when the momentum exchange is very high (see the next section on quasielastic interactions).

Seminal articles on neutrino (and electron) scattering can be found in earlier review articles by Donnelly et al. (1974), Donnelly and Walecka (1975), Donnelly and Peccei (1979), and Peccei and Donnelly (1979). Peccei and Donnelly equate the relevant form factors to those measured in ($e, e'$) scattering (Drell and Walecka, 1964; de Forest Jr. and Walecka, 1966), removing some of the model dependence and $q^2$ restrictions prevalent in certain techniques. This approach is not entirely model independent, as certain axial form factors are not completely accessible via electron scattering. This technique has been expanded in describing neutrino scattering at much higher energy scales (Amaro et al., 2005, 2007) with the recent realization that added nuclear effects come into play (Amaro et al., 2011b).

### E. Estimating fermi and Gamow-Teller strengths

For very small momentum transfers, the relevant impact of these various form factors take a back seat to the individual final states accessible to the system. Under this scheme, it is customary to divide into two general groupings: the Fermi transitions [associated with $f_V(0)$] and the Gamow-Teller transitions [associated with $f_A(0)$]. In doing so, the cross section can be rewritten as

$$\frac{d\sigma}{d\cos\theta} = G_T^2|V_{ud}|^2 F(Z, E_E) F_p P_e \left( f_P(q^2)|M_F|^2 + f_G(q^2) \frac{1}{3} |M_{GR}|^2 + \text{interference terms} \right), \quad (43)$$

where

$$|M_F|^2 = \frac{1}{2J_f + 1} \sum_{M_j, M_f} |J_f, M_f| \sum_{k=1}^A \tau_\pm(k) e^{i\phi_\tau} |J_i, M_i\rangle \langle J_i, M_i|; \quad (44)$$

$$|M_{GR}|^2 = \frac{1}{2J_f + 1} \times \sum_{M_j, M_f} |J_f, M_f| \sum_{k=1}^A \tau_\pm(k) \sigma(k) e^{i\phi_\tau} |J_i, M_i\rangle \langle J_i, M_i|; \quad (45)$$

We note that we have altered our notation slightly to denote explicit summation over individual accessible nuclear states. Equations (44) and (45) show explicitly the summation across
both initial \((|J_i, M_i|)\) and final \((|J_f, M_f|)\) spin states. In general, the terms associated with the Fermi transitions \(f_F(q^2)\) and the Gamow-Teller transitions \(f_{GT}(q^2)\) are non-trivial combinations of the various form factors described previously [see also Kuramoto et al., (1990)]. However, as one approaches zero momentum, we can immediately connect the relevant Fermi and Gamow-Teller amplitudes directly to \(\beta\) decay

\[
M_\beta = f_V(0)^2|M_F|^2 + f_A(0)^2|M_{GT}|^2,
\]

\[
|M_F|^2 = \frac{1}{2J_f + 1} \sum_{M_f, M_i} |\langle J_f, M_f | \sum_k \tau_\pm(k)|J_i, M_i\rangle|^2,
\]

\[
|M_{GT}|^2 = \frac{1}{2J_f + 1} \sum_{M_f, M_i} |\langle J_f, M_f | \sum_k \tau_\pm(k)\sigma(k)|J_i, M_i\rangle|^2,
\]

and

\[
F_I = \frac{2\pi^2}{G_F^2|V_{ud}|^2} m_e^2 M_\beta.
\]

Hence, in the most simplistic model, the total charged current cross section can be calculated directly from evaluating the appropriate \(\beta\) decay reaction and correcting for the spin of the system

\[
\sigma = \frac{2\pi^2}{m_e^2 F_I} p_e E_e F(E_e, Z_i) \frac{2J_f + 1}{2J_f + 1}.
\]

Further information on the relevant coefficients can also be obtained by studying muon capture on the nucleus of interest (Luyten, Rood, and Tolhoek, 1963; Nguyen, 1975; Ricci and Truhlik, 2010), or by imposing sum rules on the total strength of the interaction.\(^6\)

Another extremely powerful technique in helping discern the contributions to the neutrino cross section, particularly for Gamow-Teller transitions, has been through \((p, n)\) scattering. Unlike its \(\beta\) decay counterpart, \((p, n)\) scattering does not suffer from being limited to a particular momentum band; in principle, a wider band is accessible via this channel. Since the processes involved for \((p, n)\) scattering are essentially the same as those for the weak interaction in general, one can obtain an empirical evaluation of the Fermi and Gamow-Teller strengths for a given nucleus. This is particularly relevant for \((p, n)\) reactions at high incident energies and forward angles, where the direct reaction mechanism dominates. The use of \((p, n)\) reactions is particularly favorable for studying weak interaction matrix elements for a number of reasons. The reaction is naturally spin selective and spin sensitive over a wide range of beam energies. Furthermore, small angle scattering is relatively easy to prove experimentally. This approach was first explored empirically by Goodman and others (Goodman et al., 1980; Watson et al., 1985) and later expanded in a seminal paper by Taddeucci et al. (1987). Provided that \((p, n)\) forward scattering data on a particular nucleus are available, one can reduce the uncertainties on the corresponding neutrino cross section considerably. Data on \((p, n)\) scattering have been taken for a variety of nuclear targets, with particular focus on isotopes relevant for solar neutrino physics and stellar astrophysics. An example of the latter would be the treatment of the neutrino cross section at low energies for \(^{71}\)Ga (Haxton, 1998).

F. Experimental tests of low-energy cross sections on nuclei

Low-energy neutrino cross sections feature prominently in a variety of model-building scenarios. Precise knowledge of the inclusive and differential cross section feeds into reactor neutrino analysis, supernova modeling, neutrino oscillation tests, and countless others. Yet, the number of direct experimental tests of these cross sections is remarkably few. We describe some examples next.

1. Hydrogen

Inverse beta decay holds a special place for experimental neutrino physics, as it is via this channel that neutrinos were first detected (Cowan et al., 1956; Navarro, 2006). Currently, the technique of tagging inverse beta decay is prevalently used in the field for the identification and study of neutrino interactions. Inverse beta decay and neutrino absorption are still, after 60 years, the main reaction channels used for detecting reactor and solar neutrinos. Within the context of studying neutrino cross sections, however, the experimental data are somewhat limited. Most studies of neutrino interactions on protons (hydrogen) come from reactor experiments, whereby neutrinos are produced from the fission of \(^{235}\)U, \(^{239}\)Pu, \(^{241}\)Pu, and \(^{238}\)U. These experiments include Institut Laue-Langevin (ILL)-Grenoble (Kwon et al., 1981; Hounmada et al., 1995), Gösgen (Zacek et al., 1986), ROVNO (Kuvshinnikov et al., 1991), Krasnoyarsk (Vidyakin et al., 1987), and Bugey (Declais et al., 1994; Achkar et al., 1995), the latter of which had the most precise determination of the cross section. In almost all cases, the knowledge of the neutrino flux contributes the largest uncertainty. A tabulation of extracted cross sections compared to theoretical predictions is shown in Table IV. We currently omit measurements from Palo Verde (Boehm et al., 2001), CHOOZ (Apollonio et al., 2003), and KamLAND (Gando et al., 2011), as such measurements were performed at a distance greater than 100 m from the reactor core. Such distances are much more sensitive to oscillation phenomena. Also, the level of statistical precision from this latter set of experiments is lower than that from the Bugey reactor.

Because most experimental tests of inverse beta decay involve neutrinos produced from reactor sources, the conversion from the fission decays of \(^{235}\)U, \(^{239}\)Pu, \(^{239}\)U, and \(^{241}\)Pu to neutrino fluxes is extremely important. Most predictions rely on the calculations made by Schreckenbach et al. (1985).

---

\(^6\) Examples of known sum rules to this effect include the Ikeda sum rule for the Gamow-Teller strength (Ikeda, 1964)

\[
\sum_j M_{GT}^2(Z \rightarrow Z + 1)_j - M_{GT}^2(Z \rightarrow Z - 1)_j = 3(N - Z).
\]

\(^7\) The ILL experiment revised their original 1986 measurement due to better estimates of power consumption and neutrion lifetime.
TABLE IV. Measured inverse $\beta$ decay cross sections from short-baseline ($< 100$ m) reactor experiments. Data are taken from ILL-Grenoble (Kwon et al., 1981; Hoummada et al., 1995), Goesgen (Zacek et al., 1986), ROVNO (Kuvshinnikov et al., 1991), Krasnoyarsk (Vidyakin et al., 1987), and Bugey (Declais et al., 1994; Achkar et al., 1995). Theoretical predictions include original estimates and (in parenthesis) the recalculated predictions from (Mention et al., 2011).

| Experiment          | $^{238}$U | $^{239}$Pu | $^{239}$U | $^{241}$Pu | Distance (m) | $\sigma_{exp}/\sigma_{theo}$ |
|---------------------|-----------|------------|-----------|------------|--------------|-----------------------------|
| ILL (Kwon et al., 1981; Hoummada et al., 1995) | 93%       | ...        | ...       | ...        | 9            | 0.800(0.832) ± 0.028 ± 0.071 |
| Bugey (Declais et al., 1994) 94 | 53.8%     | 32.8%      | 7.8%      | 5.6%       | 15           | 0.987(0.943) ± 0.014 ± 0.027 |
| Bugey (Achkar et al., 1995) 95 | 53.8%     | 32.8%      | 7.8%      | 5.6%       | 15           | 0.988(0.943) ± 0.037 ± 0.044 |
| Bugey (Achkar et al., 1995) 95 | 53.8%     | 32.8%      | 7.8%      | 5.6%       | 40           | 0.994(0.948) ± 0.010 ± 0.045 |
| Bugey (Achkar et al., 1995) 95 | 53.8%     | 32.8%      | 7.8%      | 5.6%       | 95           | 0.915(0.873) ± 0.10 ± 0.041 |
| Goesgen (Zacek et al., 1986) 1 | 61.9%     | 27.2%      | 6.7%      | 4.2%       | 37.9         | 1.018(0.971) ± 0.017 ± 0.06 |
| Goesgen (Zacek et al., 1986) II | 58.4%     | 29.8%      | 6.8%      | 5.0%       | 45.9         | 1.045(0.997) ± 0.019 ± 0.06 |
| Goesgen (Zacek et al., 1986) III | 54.3%     | 32.9%      | 7.0%      | 5.8%       | 64.7         | 0.975(0.930) ± 0.033 ± 0.06 |
| ROVNO (Kuvshinnikov et al., 1991) | 61.4%     | 27.5%      | 3.1%      | 7.4%       | 18           | 0.985(0.940) ± 0.028 ± 0.027 |
| Krasnoyarsk (Vidyakin et al., 1987) I | 99%       | ...        | ...       | ...        | 33           | 1.013(0.944) ± 0.051 |
| Krasnoyarsk (Vidyakin et al., 1987) II | 99%       | ...        | ...       | ...        | 57           | 0.989(0.954) ± 0.041 |
| Krasnoyarsk (Vidyakin et al., 1987) III | 99%       | ...        | ...       | ...        | 33           | 1.031(0.960) ± 0.20  |

Recently, a new calculation of the antineutrino spectrum has emerged which incorporates a more comprehensive model of fission production (Mueller et al., 2011). The new method, which is well constrained by the accompanying electron spectrum measured from fission, has the effect that it systematically raises the expected antineutrino flux from reactors (Mention et al., 2011), providing some tension between the data and theoretical predictions. The new calculation is still under evaluation. In our review, we list both the shifted and unshifted cross section ratios (see Table IV and Fig. 5).

![FIG. 5](color online). Compilation of world reactor data for neutrino inverse beta decay processes for distances $\leq 100$ m based on former (left) and new (right) theoretical flux predictions. The error on the neutron lifetime is shown for comparison. From Mention et al., 2011.)

Rev. Mod. Phys., Vol. 84, No. 3, July–September 2012
TABLE V. Measured charged current ($\bar{\nu}_e$CC) and neutral-current ($\bar{\nu}_e$NC) neutrino cross sections on deuterium from short-baseline ($<100\text{ m}$) reactor experiments. Data are taken from Savannah River (Pasierb et al., 1979), ROVNO (Vershinsky et al., 1991), Krasnoyarsk (Riley et al., 1999; Kozlov et al., 2000), and Bugey (Riley et al., 1999). The comparison with theory is from Kozlov et al. (2000).

| Experiment                                    | Measurement | $\sigma_{\text{fission}}$ (10^{-24}\text{ cm}^2/\text{fission}) | $\sigma_{\exp}/\sigma_{\text{theory}}$ |
|-----------------------------------------------|-------------|-----------------------------------------------------------------|-----------------------------------------|
| Savannah River (Pasierb et al., 1979)         | $\bar{\nu}_e$CC | 1.5 ± 0.4                                                         | 0.7 ± 0.2                               |
| ROVNO (Vershinsky et al., 1991)               | $\bar{\nu}_e$CC | 1.17 ± 0.16                                                       | 1.08 ± 0.19                             |
| Krasnoyarsk (Kozlov et al., 2000)             | $\bar{\nu}_e$CC | 1.05 ± 0.12                                                       | 0.98 ± 0.18                             |
| Bugey (Riley et al., 1999)                    | $\bar{\nu}_e$CC | 0.95 ± 0.20                                                       | 0.97 ± 0.20                             |
| Savannah River (Pasierb et al., 1979)         | $\bar{\nu}_e$NC | 3.8 ± 0.9                                                         | 0.8 ± 0.2                               |
| ROVNO (Vershinsky et al., 1991)               | $\bar{\nu}_e$NC | 2.71 ± 0.47                                                       | 0.92 ± 0.18                             |
| Krasnoyarsk (Kozlov et al., 2000)             | $\bar{\nu}_e$NC | 3.09 ± 0.30                                                       | 0.95 ± 0.33                             |
| Bugey (Riley et al., 1999)                    | $\bar{\nu}_e$NC | 3.15 ± 0.40                                                       | 1.01 ± 0.13                             |

2. Deuterium

Direct tests of low-energy neutrino interactions on deuterium are of particular importance for both solar processes and solar oscillation probes. The Sudbury Neutrino Observatory stands as the main example, as it uses heavy water as its solar oscillation probes. The Sudbury Neutrino Observatory, ROVNO, and Bugey have also been carried out using antineutrinos produced in stopped pions created at their 720 MeV proton beam stops (Willis et al., 1980). The cross section is averaged over the Michel muon decay spectrum. Their reported measurement of $\langle \sigma_{\nu} \rangle = (0.52 ± 0.18) \times 10^{-40}\text{ cm}^2$ is in good agreement with theoretical predictions.

Direct cross section measurements on deuterium targets have also been carried out using antineutrinons produced in nuclear reactors. Reactor experiments, including Savannah River (Reines, Gurr, and Sobel, 1976), ROVNO (Vershinsky et al., 1991), Krasnoyarsk (Kozlov et al., 2000), and Bugey (Riley et al., 1999), have reported cross sections per fission for both charged current ($\bar{\nu}_e d \rightarrow e^- p p$) and neutral-current ($\bar{\nu}_e d \rightarrow e^- n n$) reactions (see Table V).

As we proceed to other nuclear targets, one immediately appreciates the rarity of this state.

3. Additional nuclear targets

The other main nuclear isotope studied in detail is $^{12}$C. There are a number of neutrino interactions on $^{12}$C that have been investigated experimentally

$$\nu_{e,\mu} + ^{12}\text{C}_{g.s.} \rightarrow (e^-, \mu^-) + ^{12}\text{N}_{g.s.}$$

(exclusive charged current).

$$\nu_{e,\mu} + ^{12}\text{C}_{g.s.} \rightarrow (e^-, \mu^-) + ^{12}\text{N}^*$$

(inclusive charged current).

$$\nu + ^{12}\text{C}_{g.s.} \rightarrow \nu + ^{12}\text{C}^*$$

(neutral current).

Reaction (51) is a uniquely clean test case for both theory and experiment. The spin parity of the ground state of $^{12}$C is $J^P = 0^+$, $T = 0$, while for the final state it is $J^P = 1^+, T = 1$. As such, there exists both an isospin and spin flip in the interaction, the former involving the isovector components of the reaction, while the latter involving the axial-vector components. Therefore, both vector and axial-vector components contribute strongly to the interaction. The isovector components are well constrained by electron scattering data. Since the final state of the nucleus is also well defined, the axial form factors can be equally constrained by looking at the $\beta$ decay of $^{12}$N, as well as the muon capture on $^{12}$C. Although these constraints occur at a specific momentum transfer, they provide almost all necessary information to calculate the cross section. The exclusive reaction is also optimal from an experimental perspective. The ground state of $^{12}$N beta decays to the ground state of $^{12}$C with a half-life of 11 ms; the emitted secondary electron providing a well-defined tag for event identification. The neutral-current channel has an

As we proceed to other nuclear targets, one immediately appreciates the rarity of this state.

### Table VI. Extraction of the isovector axial two-body current parameter $L_{1A}$ from various experimental constraints.

| Method          | Extracted $L_{1A}$ (fm$^3$) |
|-----------------|-------------------------------|
| Reactor         | 3.6 ± 5.5                     |
| Solar           | 4.0 ± 6.3                     |
| Helioseismology | 4.8 ± 6.7                     |
| $^3\text{He} \rightarrow ^3\text{H} e^- \bar{\nu}_e$ | 6.5 ± 2.4                    |
Table VII. Experimentally measured (flux-averaged) cross sections on various nuclei at low energies (1–300 MeV). Experimental data gathered from the LAMPF (Willis et al., 1980), KARMEN (Bodmann et al., 1991; Zeitnitz et al., 1994; Armbruster et al., 1998; Maschuw, 1998; Ruf, 2005), E225 (Kraukauer et al., 1992), LSND (Athanassopoulos et al., 1997; Auerbach et al., 2001; Auerbach et al., 2002; Distel et al., 2003), GALLEX (Hampel et al., 1998), and SAGE (Abdurashitov et al., 1999; Abdurashitov et al., 2006) experiments. Stopped $\pi/\mu$ beams can access neutrino energies below 53 MeV, while decay-in-flight measurements can extend up to 300 MeV. The $^{51}$Cr sources have several monoenergetic lines around 430 and 750 keV, while the $^{37}$Ar source has its main monoenergetic emission at $E_\nu = 811$ keV. Selected comparisons to theoretical predictions, using different approaches are also listed. The theoretical predictions are not meant to be exhaustive.

| Isotope | Reaction Channel | Source | Experiment | Measurement (10^{-42} cm^2) | Theory (10^{-42} cm^2) |
|---------|------------------|--------|------------|-----------------------------|-------------------------|
| $^2H$   | $^2H(\nu_e, e^-)pp$ | Stopped $\pi/\mu$ | LAMPF | 52 $\pm$ 18 (tot) | 54 (IA) (Tatare, Kohnyma, and Kubodera, 1990) |
| $^{12}C$ | $^{12}C(\nu_e, e^-)^{12}N_{gs}$ | Stopped $\pi/\mu$ | KARMEN | 9.1 $\pm$ 0.5 (stat) $\pm$ 0.8 (sys) | 9.4 [Multipole] (Donnelly and Peccci, 1979) |
|         |                  | Stopped $\pi/\mu$ | E225 | 10.5 $\pm$ 1.0 (stat) $\pm$ 1.0 (sys) | 9.2 [EPT] (Fukugita, Kohnyma, and Kubodera, 1988). |
| $^{12}C$ | $^{12}C(\nu_e, e^-)^{12}N^*$ | Stopped $\pi/\mu$ | LSND | 8.9 $\pm$ 0.3 (stat) $\pm$ 0.9 (sys) | 8.9 [CRPA] (Kolbe, Langanke, and Vogel, 1999) |
|         |                  | Stopped $\pi/\mu$ | KARMEN | 5.1 $\pm$ 0.6 (stat) $\pm$ 0.5 (sys) | 5.4–5.6 [CRPA] (Kolbe, Langanke, and Vogel, 1999) |
| $^{56}Fe$ | $^{56}Fe(\nu_e, e^-)^{56}Co$ | Stopped $\pi/\mu$ | KARMEN | 256 $\pm$ 108 (stat) $\pm$ 43 (sys) | 68–73 [CRPA] (Kolbe, Langanke, and Vogel, 1999) |
| $^{71}Ga$ | $^{71}Ga(\nu_e, e^-)^{71}Ge$ | $^{51}Cr$ source | GALLEX, ave. | 0.0054 $\pm$ 0.0009 (tot) | 0.0055 $\pm$ 0.0007 (tot) |
|         |                  | $^{51}Cr$ | SAGE | 0.0055 $\pm$ 0.0007 (tot) | 0.0058 [Shell] (Haxton, 1998) |
| $^{127}I$ | $^{127}I(\nu_e, e^-)^{127}Xe$ | Stopped $\pi/\mu$ | LSND | 284 $\pm$ 91 (stat) $\pm$ 25 (sys) | 0.0070 [Shell] (Bahcall, 1997) |

Equally favorable channel, with the emission of a monoenergetic 15.11 MeV photon.

Studies of the above neutrino cross sections have been carried out at the LAMPF facility in the United States (Willis et al., 1980) and the Karlsruhe Rutherford Medium Energy Neutrino Experiment (KARMEN) detector at ISIS at the Rutherford Laboratory in the United Kingdom. The neutrino beam in both experimental facilities is provided from proton beam stops. High-energy proton collisions on a fixed target produce a large $\pi^+$ flux which is subsequently stopped and allowed to decay. The majority of low-energy neutrinos are produced from the decay at rest from stopped $\mu^+$ and $\pi^+$, providing a well-characterized neutrino beam with energies below 50 MeV. The KARMEN experiment at the ISIS facility additionally benefited from a well-defined proton beam structure, which allowed efficient tagging of neutrino events against cosmic ray backgrounds. The main uncertainty affecting these cross section measurements stems primarily from the knowledge of the pion flux produced in the proton-target interactions.

Table VII summarizes the measurements to date on the inclusive and exclusive reactions on $^{12}C$ at low energies. Estimates of the cross sections using a variety of different techniques (shell model, RPA, QRPA, effective particle theory) demonstrate the robustness of the calculations. Some disagreement can be seen in the inclusive channels; this disagreement is to be expected since the final state is not as well defined as in the exclusive channels. More recent predictions employing extensive shell model calculations appear to show better agreement with the experimental data. A plot showing the collected data from the exclusive reaction $^{12}C(\nu_e, e^-)^{12}N$ and $^{12}C(\nu_\mu, e^-)^{12}N$ are shown in Figs. 6 and 7, respectively.

Table VII also lists other nuclei that have been used in the high-energy neutrino cross sections on $^{127}I$. Cross sections on iron targets have also been explored with low-energy beams at the KARMEN experiment (Ruf, 2005).

Perhaps the most remarkable of such measurements was the use of MCI radiological sources for low-energy electron cross section measurements. Both the Soviet-American Gallium Experiment (SAGE) (Abdurashitov et al., 1999) and GALLium EXperiment (GALLEX) (Anselmann et al., 1995) solar neutrino experiments have made use of a MCI $^{51}Cr$ source to study the reaction $^{71}Ga(\nu_e, e^-)^{71}Ge$ to both the ground and excited states of $^{71}Ge$. The source strength of $^{51}Cr$ is typically determined using calorimetric techniques and the uncertainty on the final activity is constrained to about 1%–2%. The SAGE collaboration subsequently also made use of a gaseous $^{37}Ar$MCI source. Its activity, using a...
variety of techniques, is constrained to better than 0.5% (Haxton, 1998; Barsanov et al., 2007). Since $^{37}$Ar provides a monoenergetic neutrino at slightly higher energies that its $^{51}$Cr counterpart, it provides a much cleaner check on the knowledge of such low-energy cross sections (Barsanov et al., 2007). Experimental measurements are in general in agreement with the theory, although the experimental values are typically lower than the corresponding theoretical predictions.

Finally, although the cross section was not measured explicitly using a terrestrial source, neutrino capture on chlorine constitutes an important channel used in experimental neutrino physics. The reaction $^{37}$Cl($\nu_e, e^-$)$^{37}$Ar was the first reaction used to detect solar neutrinos (Cleveland et al., 1998).

In summary, the level at which low-energy cross sections are probed using nuclear targets is relatively few, making the ability to test the robustness of theoretical models and techniques somewhat limited. The importance of such low-energy cross sections is continually stressed by advances in astrophysics, particularly in the calculation of elemental abundances and supernova physics (Langanke et al., 2004; Heger et al., 2005). Measurements of neutrino cross sections on nuclear targets is currently being revisited now that new high intensity stopped pion and muon sources are once again becoming available (Avignone et al., 2000).

G. Transitioning to higher energy scales

As we transition from low-energy neutrino interactions to higher energies, the reader may notice that our approach is primarily focused on the scattering off a particular target, whether that target be a nucleus, a nucleon, or a parton. This approach is not accidental, as it is theoretically a much more well-defined problem when the target constituents are treated individually. With that said, we acknowledge that the approach is also limited, as it fails to incorporate the nucleus as a whole. Such departmentalization is part of the reason why the spheres of low-energy and high-energy physics appear so disjointed in both approach and terminology. Until a full, comprehensive model of the entire neutrino-target interaction is formulated, we are constrained to also follow this approach.

V. INTERMEDIATE ENERGY CROSS SECTIONS: $E_{\nu} \sim 0.1-20$ GeV

As we move up farther still in energy, the description of neutrino scattering becomes increasingly more diverse and complicated. At these intermediate energies, several distinct neutrino scattering mechanisms start to play a role. The possibilities fall into three main categories:

- **Elastic and quasielastic scattering**: Neutrinos can elastically scatter off an entire nucleon liberating a nucleon (or multiple nucleons) from the target. In the case of charged current neutrino scattering, this process is referred to as “quasielastic scattering” and is a mechanism we first alluded to in Sec. IV.D, whereas for neutral-current scattering this is traditionally referred to as “elastic scattering.”
- **Resonance production**: Neutrinos can excite the target nucleon to a resonance state. The resultant baryonic resonance ($\Delta, N'$) decays to a variety of possible mesonic final states producing combinations of nucleons and mesons.
- **Deep inelastic scattering**: Given enough energy, the neutrino can resolve the individual quark constituents of the nucleon. This is called deep inelastic scattering and manifests in the creation of a hadronic shower.

As a result of these competing processes, the products of neutrino interactions include a variety of final states ranging from the emission of nucleons to more complex final states including pions, kaons, and collections of mesons (Fig. 8). This energy regime is often referred to as the “transition region” because it corresponds to the boundary between quasielastic scattering (in which the target is a nucleon) on the one end and deep inelastic scattering (in which the target is the constituent parton inside the nucleon) on the other. Historically, adequate theoretical descriptions of quasielastic, resonance-mediated, and deep inelastic scattering have been formulated; however, there is no uniform description which...
globally describes the transition between these processes or how they should be combined. Moreover, the full extent to which nuclear effects impact this region is a topic that has only recently been appreciated. Therefore, in this section, we focus on what is currently known, both experimentally and theoretically, about each of the exclusive final-state processes that participate in this region.

To start, Fig. 9 summarizes the existing measurements of CC neutrino and antineutrino cross sections across this intermediate energy range

\[ \nu_\mu N \rightarrow \mu^- X, \]  

\[ \bar{\nu}_\mu N \rightarrow \mu^+ X. \]  

These results have been accumulated over many decades using a variety of neutrino targets and detector technologies. We immediately notice three things from this figure. First, the total cross sections approach a linear dependence on neutrino energy as the neutrino energy increases.

![FIG. 8. Predicted processes to the total CC inclusive scattering cross section at intermediate energies. The underlying quasileptonic, resonance, and deep inelastic scattering contributions can produce a variety of possible final states including the emission of nucleons, single pions, multipions, kaons, as well as other mesons (not shown). Combined, the inclusive cross section exhibits a linear dependence on neutrino energy as the neutrino energy increases.](image1)

![FIG. 9. Total neutrino and antineutrino per nucleon CC cross sections (for an isoscalar target) divided by neutrino energy and plotted as a function of energy. Data are the same as in Figs. 28, 11, and 12, with the inclusion of additional lower energy CC inclusive data from \( \Delta \) (Baker et al., 1982), * (Baranov et al., 1979), ■ (Ciampolillo et al., 1979), and * (Nakajima et al., 2011). Also shown are the various contributing processes that will be investigated in the remaining sections of this review. These contributions include quasileptonic scattering (dashed), resonance production (dotted), and deep inelastic scattering (dotted). Example predictions for each are provided by the NUANCE generator (Casper, 2002). Note that the quasileptonic scattering data and predictions have been averaged over neutron and proton targets and hence have been divided by a factor of 2 for the purposes of this plot.](image2)

the 1970s and 1980s using either bubble chamber or spark chamber detectors and represent a large fraction of the data presented in the summary plots we show. Over the years, interest in this energy region waned as efforts migrated to higher energies to yield larger event samples and the focus centered on measurement of electroweak parameters (\( \sin^2 \theta_W \)) and structure functions in the deep inelastic scattering region. With the discovery of neutrino oscillations and the advent of higher intensity neutrino beams, however, this situation has been rapidly changing. The processes discussed here are important because they form some of the dominant signal and background channels for experiments searching for neutrino oscillations. This is especially true for experiments that use atmospheric or accelerator-based sources of neutrinos. With a view to better understanding these neutrino cross sections, new experiments such as Argon Neutrino Test (ArgoNeuT), KEK to Kamioka (K2K), Mini Booster Neutrino Experiment (MiniBooNE), Main Injector ExpeRiment: nu-A (MINER\( \nu \)A), Main Injector Neutrino Oscillation Search (MINOS), Neutrino
Oscillation MAgnetic Detector (NOMAD), SciBar Booster Neutrino Experiment (SciBooNE), and Tokai to Kamioka experiment (T2K) have started to study this intermediate energy region in greater detail. New theoretical approaches have also recently emerged.

We start by describing the key processes which can contribute to the total cross section at these intermediate neutrino energies. Here we focus on several key processes: quasielastic, NC elastic scattering, resonant single pion production, coherent pion production, multipion production, and kaon production before turning our discussion to deep inelastic scattering in the following section on high-energy neutrino interactions. For comparison, we also include predictions from the NUANCE event generator (Casper, 2002), chosen as a representative of the type of models used in modern neutrino experiments to describe this energy region. The bulk of our discussions center around measurements of $\nu_\mu$-nucleon scattering. Many of these arguments also carry over to $\nu_\tau$ scattering, except for one key difference; the energy threshold for the reaction. Unlike for the muon case, the charged current $\nu_\tau$ interaction cross section is severely altered because of the large $\tau$ lepton mass. Figure 10 reflects some of the large differences in the cross section that come about due to this threshold energy.

A. Quasielastic scattering

For neutrino energies less than $\sim$2 GeV, neutrino-hadron interactions are predominantly quasielastic (QE), hence they provide a large source of signal events in many neutrino oscillation experiments operating in this energy range. In a QE interaction, the neutrino scatters off an entire nucleon rather than its constituent partons. In a charged current neutrino QE interaction, the target neutron is converted to a rather than its constituent partons. In a charged current QE interaction, the neutrino scatters off an entire nucleon oscillation experiments operating in this energy range. In a charged current QE interaction, the neutrino scatters off an entire nucleon.

For neutrino energies less than $\sim$2 GeV, neutrino-hadron interactions are predominantly quasielastic (QE), hence they provide a large source of signal events in many neutrino oscillation experiments operating in this energy range. In a QE interaction, the neutrino scatters off an entire nucleon rather than its constituent partons. In a charged current neutrino QE interaction, the target neutron is converted to a neutron, $\nu_\mu n \rightarrow \mu^- p$, $\bar{\nu}_\mu p \rightarrow \mu^+ n$.

Such simple interactions were extensively studied in the 1970s–1990s primarily using deuterium-filled bubble chambers. The main interest at the time was in testing the vector-axial-vector form factor at $Q^2 = 0$, $g_A = F_A(0) = 1.2694 \pm 0.0028$ (Nakamura, K., et al., 2010), and an “axial mass” $M_A$.

In predicting the QE scattering cross section, early experiments relied heavily on the formalism first written down in Llewellyn-Smith (1972). In the case of QE scattering off free nucleons, the QE differential cross section can be expressed as

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 M^2}{8\pi E_\nu^2} \left[ A \pm \frac{s - u}{M^2} B + \frac{(s - u)^2}{M^4} C \right].$$

where $(-)^+$ refers to (anti)neutrino scattering, $G_F$ is the Fermi coupling constant, $Q^2$ is the squared four-momentum transfer ($Q^2 = -q^2 > 0$), $M$ is the nucleon mass, $m$ is the lepton mass, $E_\nu$ is the incident neutrino energy, and $s - u = 4M E_\nu - Q^2 - m^2$. The factors $A$, $B$, and $C$ are functions of the familiar vector ($F_1$ and $F_2$), axial-vector ($F_A$), and pseudoscalar ($F_P$) form factors of the nucleon

$$A = \frac{m^2 + Q^2}{M^2} \left[ (1 + \eta) F_A^2 - (1 - \eta) F_1^2 + \eta(1 - \eta) F_2^2 \right] + 4\eta F_1 F_2 - \frac{m^2}{4M^2} \left( F_1 + F_2 \right)^2 + \left( \frac{Q^2}{M^2} + 4 \right) F_P^2 \right]\right].$$

$$B = \frac{Q^2}{M^2} F_A(F_1 + F_2),$$

$$C = \frac{1}{4} \left( F_A^2 + F_1^2 + \eta F_2^2 \right).$$

where $\eta = Q^2/4M^2$. Much of these equations should be familiar from Sec. IV. Historically, this formalism was used to analyze neutrino QE scattering data on deuterium, subject to minor modifications for nuclear effects. In this way, experiments studying neutrino QE interaction could in principle measure the vector, axial-vector, and pseudoscalar form factors given that the weak hadronic current contains all three of these components. In practice, the pseudoscalar contribution was typically neglected in the analysis of $\nu_\mu$ QE scattering as it enters the cross section multiplied by $m^2/M^2$. Using CVC, the vector form factors could be obtained from electron scattering, thus leaving the neutrino experiments to measure the axial-vector form factor of the nucleon. For the axial-vector form factor, it was (and still is) customary to assume a dipole form

$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2},$$

which depends on two empirical parameters: the value of the axial-vector form factor at $Q^2 = 0$, $g_A = F_A(0) = 1.2694 \pm 0.0028$ (Nakamura, K., et al., 2010), and an “axial mass” $M_A$.

With the vector form factors under control from electron scattering and $g_A$ determined with high precision from nuclear beta decay, measurement of the axial-vector form factor (and hence $M_A$) became the focus of the earliest

![Plot comparing the total charged current $\nu_\mu$ (solid) and $\nu_\tau$ (dashed) per nucleon cross sections divided by neutrino energy and plotted as a function of neutrino energy.](image-url)
measurements of neutrino QE scattering. Values of $M_A$ ranging from 0.65 to 1.09 GeV were obtained in the period from the late 1960s to early 1990s resulting from fits to both the total rate of observed events and the shape of their measured $Q^2$ dependence [for a recent review, see Lyubushkin et al. (2009)]. In addition to providing the first measurements of $M_A$ and the QE cross section, many of these experiments also performed checks of CVC, fit for the presence of second-class currents, and experimented with different forms for the axial-vector form factor. By the end of this period, the neutrino QE cross section could be accurately and consistently described by V-A theory assuming a dipole axial-vector form factor with $M_A = 1.026 \pm 0.021$ GeV (Bernard et al., 2002). These conclusions were largely driven by experimental measurements on deuterium, but less-precise data on other heavier targets also contributed. More recently, some attention has been given to reanalyzing these same data using modern vector form factors as input. The use of updated vector form factors slightly shifts the best-fit axial mass values obtained from these data; however, the conclusion is still that $M_A \sim 1.0$ GeV.

Modern day neutrino experiments no longer include deuterium but use complex nuclei as their neutrino targets. As a result, nuclear effects become much more important and produce sizable modifications to the QE differential cross section from Eq. (57). With QE events forming the largest contribution to signal samples in many neutrino oscillation experiments, there has been renewed interest in the measurement and modeling of QE scattering on nuclear targets. In such situations, the nucleus is typically described in terms of individual quasi-free nucleons that participate in the scattering process (the so-called “impulse approximation” approach) (Frullani and Mougey, 1984). Most neutrino experiments use a relativistic Fermi-gas model (Smith and Moniz, 1972) when simulating their QE scattering events, although many other independent particle approaches have been developed in recent years that incorporate more sophisticated treatments. These include spectral function (Nakamura and Seki, 2002; Benhar et al., 2005; Ankowski and Sobczyk, 2006; Benhar and Meloni, 2007; Juszczak, Sobczyk, and Zmuda, 2010), superscaling (Amaro et al., 2005), RPA (Nieves, Amaro, and Valverde, 2004; Nieves, Valverde, and Vicente Vacas, 2006; Leitner and Mosel, 2009; Sajjad Athar, Chauhan, and Singh, 2010), and plane-wave impulse approximation-based calculations (Butkevich, 2010). In concert, the added nuclear effects from these improved calculations tend to reduce the predicted neutrino QE cross section beyond the Fermi-gas model-based predictions. These reductions are typically on the order of 10%–20% (Alvarez-Ruso, 2010).

Using Fermi-gas model-based simulations and analyzing higher statistics QE data on a variety of nuclear targets, new experiments have begun to repeat the axial-vector measurements that fueled much of the early investigations of QE scattering. Axial mass values ranging from 1.05 to 1.35 GeV have been recently obtained (Gran et al., 2006; Espinal and Sanchez, 2007; Aguilar-Arevalo, 2008, 2010a; Dorman, 2009; Lyubushkin et al., 2009), with most of the experiments systematically measuring higher $M_A$ values than those found in the deuterium fits. This has recently sparked some debate, especially given that higher $M_A$ values naturally imply higher cross sections and hence larger event yields for neutrino experiments.10 We return to this point later.

Neutrino experiments have also begun to remeasure the absolute QE scattering cross section making use of more reliable incoming neutrino fluxes made available in modern experimental setups. Figure 11 summarizes the existing measurements of $\nu_{\mu}$ QE scattering cross sections as a function of neutrino energy from both historical and recent measurements. As expected, we observe a linearly rising cross section that is damped by the form factors at higher neutrino energies. What is not expected is the disparity observed between recent measurements. High statistics measurements of the QE scattering cross section by the MiniBooNE (Aguilar-Arevalo et al., 2010a) and NOMAD (Lyubushkin et al., 2009) experiments, both on carbon, appear to differ in normalization by about 30%. The low-energy MiniBooNE results are higher than expected from the Fermi-gas model (Smith and Moniz, 1972) and more sophisticated impulse approximation calculations (Frullani and Mougey, 1984; Maieron et al., 2003; Nieves, Amaro, and Valverde, 2004; Leitner et al., 2006; Martinez et al., 2006; Nieves et al., 2006; Benhar and Meloni, 2007; Ankowski and Sobczyk, 2008; Butkevich, 2009; Leitner et al., 2009; Athar et al., 2010) assuming an axial mass, $M_A = 1.0$ GeV, from deuterium-based measurements as input.

How can it be that new, high statistics measurements of this simple process are not coming out as expected? The fact that modern measurements of QE scattering have seemingly
raised more questions than they have answered has been recently noted (Gallagher, Garvey, and Zeller, 2011; Sobczyk, 2011). It is currently believed that nuclear effects beyond the impulse approximation approach are responsible for the discrepancies noted in the experimental data. In particular, it is now being recognized that nucleon-nucleon correlations and two-body exchange currents must be included in order to provide a more accurate description of neutrino-nucleus QE scattering. These effects yield significantly enhanced cross sections (larger than the free scattering case) which, in some cases, appear to better match the experimental data (Aguilar-Arevalo et al., 2010a) at low neutrino energies (Amaro et al., 2011b; Barbaro et al., 2011; Bodek and Budd, 2011; Giusti and Meucci, 2011; Martini, Ericson, and Chanfray, 2011; Nieves, Ruiz-Simo, and Vicente-Vacas, 2011; Sobczyk, 2012). They also produce final states that include multiple nucleons, especially when it comes to scattering off of nuclei. The final state need not just include a single nucleon, hence why one needs to be careful in defining a “quasielastic” event especially when it comes to scattering off of nuclei.

In hindsight, the increased neutrino QE cross sections and harder $Q^2$ distributions (high $M_A$) observed in much of the experimental data should probably have not come as a surprise. Such effects were also measured in transverse electron-nucleus quasielastic scattering many years prior (Carlson, 2002). The possible connection between electron and neutrino QE scattering observations has only been recently appreciated. Today, the role that additional nuclear effects may play in neutrino-nucleus QE scattering remains the subject of much theoretical and experimental scrutiny. Improved theoretical calculations and experimental measurements are already underway. As an example, the first double differential cross section distributions for $\nu$ QE scattering were recently reported by the MiniBooNE experiment (Aguilar-Arevalo et al., 2010a). It is generally recognized that such model-independent measurements are more useful than comparing $M_A$ values. Such differential cross section data are also providing an important new testing ground for improved nuclear model calculations (Amaro et al., 2011a; Giusti and Meucci, 2011; Martini, Ericson, and Chanfray, 2011; Nieves, Simo, and Vacas, 2012; Sobczyk, 2012). Moving forward, additional differential cross section measurements, detailed measurements of nucleon emission, and studies of antineutrino QE scattering are needed before a solid description can be secured.

So far we have focused on neutrino QE scattering. Figure 12 shows the status of measurements of the corresponding antineutrino QE scattering cross section. Recent results from the NOMAD experiment have expanded the reach out to higher neutrino energies, however, there are currently no existing measurements of the antineutrino QE scattering cross section below 1 GeV. Given that the newly appreciated effects of nucleon-nucleon correlations are expected to be different for neutrinos and antineutrinos, a high priority has been recently given to the study of antineutrino QE scattering at these energies. A precise handle on neutrino and antineutrino QE interaction cross sections will be particularly important in the quest for the detection of $CP$ violation in the leptonic sector going into the future.

Up to now, we discussed the case where nucleons can be ejected in the elastic scattering of neutrinos from a given target. The final state is traditionally a single nucleon, but can also include multiple nucleons, especially in the case of neutrino-nucleus scattering. For antineutrino QE scattering, it should be noted that the Cabibbo-suppressed production of hyperons is also possible, for example,

$$\bar{\nu}_\mu p \rightarrow \mu^+ \Lambda^0,$$  

$$\bar{\nu}_\mu n \rightarrow \mu^+ \Sigma^-,$$  

$$\bar{\nu}_\mu p \rightarrow \mu^+ \Sigma^0.$$  

Cross sections for QE hyperon production by neutrinos were calculated very early on (Cabibbo and Chilton, 1965; Llewellyn-Smith, 1972) and verified in low statistics measurements by a variety of bubble chamber experiments (Eichten et al., 1972; Erriques et al., 1977; Ammosov et al., 1987; Brunner et al., 1990). New calculations have also recently surfaced (Singh and Vacas, 2006; Mintz and Wen, 2007; Kuzmin and Naumov, 2009). We will say more about strange particle production later when we discuss kaon production (Sec. V.F).

Combined, all experimental measurements of QE scattering cross sections have been conducted using beams of muon neutrinos and antineutrinos. No direct measurements of $\nu_e$ or $\bar{\nu}_e$ QE scattering cross sections have yet been performed at these energies.

### B. NC elastic scattering

Neutrinos can also elastically scatter from nucleons via neutral-current (NC) interactions

$$\nu p \rightarrow \nu p, \quad \bar{\nu} p \rightarrow \bar{\nu} p,$$  

$$\nu n \rightarrow \nu n, \quad \bar{\nu} p \rightarrow \bar{\nu} p.$$  

Equations (57)–(60) still apply in describing NC elastic scattering from free nucleons with the exception that, in this case, the form factors include additional coupling factors and a contribution from strange quarks.
\[ F_1(Q^2) = \left( \frac{1}{2} - \sin^2 \theta_W \right) \left[ \frac{\tau_3[1 + \eta(1 + \mu_p - \mu_n)]}{(1 + \eta)(1 + \frac{Q^2}{M_V^2})^2} \right] - \sin^2 \theta_W \left[ \frac{1 + \eta(1 + \mu_p + \mu_n)}{(1 + \eta)(1 + \frac{Q^2}{M_V^2})^2} \right] - \frac{F_1(Q^2)}{2} F_2(Q^2) \]

\[ = \left( \frac{1}{2} - \sin^2 \theta_W \right) \frac{\tau_3(\mu_p - \mu_n)}{(1 + \eta)(1 + \frac{Q^2}{M_V^2})^2} - \sin^2 \theta_W \frac{\mu_p + \mu_n}{(1 + \eta)(1 + \frac{Q^2}{M_V^2})^2} - \frac{F_1^3(Q^2)}{2} F_2(Q^2) \]

\[ = \frac{g_A \tau_3}{2(1 + \frac{Q^2}{M_A^2})^2} - \frac{F_A^3(Q^2)}{2}, \quad (67) \]

where \( \Delta s \) is the strange quark contribution to the nucleon spin and \( M_A \) is the same axial mass appearing in the expression for CC QE scattering [Eq. (61)].

Over the years, experiments typically measured NC elastic cross section ratios with respect to QE scattering to help minimize systematics. Table VIII lists a collection of historical measurements of the NC elastic and QE cross section ratio \( v\mu p \rightarrow v\mu p / v\mu n \rightarrow \mu^- p \). These ratios have been integrated over the kinematic range of the experiment. More recently, the MiniBooNE experiment measured the NC elastic and QE ratio on carbon in bins of \( Q^2 \) (Aguilar-Arevalo et al., 2010b).

Experiments such as BNL E734 and MiniBooNE have additionally reported measurements of flux-averaged absolute differential cross sections \( d\sigma/dQ^2 \) for NC elastic scattering on carbon. From these distributions, measurements of parameters appearing in the cross section for this process, \( M_A \) and \( \Delta s \), can be directly obtained. Table IX summarizes those findings. As with QE scattering, a new appreciation for the presence of nuclear effects in such neutral-current interactions has also recently arisen with many new calculations of this cross section on nuclear targets (Amaro et al., 2006; Benhar and Veneziano, 2011; Butkevich and Perevalov, 2011; Meucci, Giusti, and Pacati, 2011). Just as in the charged current case, nuclear corrections can be on the order of 20% or more.

### TABLE VIII. Measurements of the ratio \( v\mu p \rightarrow v\mu p / v\mu n \rightarrow \mu^- p \) taken from BNL E734 (Faissner et al., 1980; Coteus et al., 1981; Ahrens et al., 1988), BNL E613 (Entenberg et al., 1979), and Gargamelle (Pohl et al., 1978). Also indicated is the \( Q^2 \) interval over which the ratio was measured.

| Experiment | Target | Ratio | \( Q^2(\text{GeV}^2) \) |
|------------|--------|-------|----------------------|
| BNL E734   | CH\textsubscript{2} | 0.153 ± 0.018 | 0.5–1.0 |
| BNL CIB    | Al     | 0.11 ± 0.03  | 0.3–0.9 |
| Aachen     | Al     | 0.10 ± 0.03  | 0.2–1.0 |
| BNL E613   | CH\textsubscript{2} | 0.11 ± 0.02  | 0.4–0.9 |
| Gargamelle | CF\textsubscript{3}Br | 0.12 ± 0.06  | 0.3–1.0 |

### TABLE IX. Measurements of the axial mass and strange quark content to the nucleon spin from neutrino NC elastic scattering data from BNL E734 (Ahrens et al., 1988) and MiniBooNE (Aguilar-Arevalo et al., 2010b). BNL-E734 reported a measurement of \( \eta = 0.12 ± 0.07 \) which implies \( \Delta s = -g_A \eta = -0.15 ± 0.09 \). Note that updated fits to the BNL-E734 data were also later performed by several groups (Garvey et al., 1993; Alberico et al., 1999).

| Experiment | \( M_A \) (GeV) | \( \Delta s \) |
|------------|----------------|--------------|
| BNL E734   | 1.06 ± 0.05    | −0.15 ± 0.09 |
| MiniBooNE  | 1.39 ± 0.11    | 0.08 ± 0.26  |

C. Resonant single pion production

Now that we discussed quasielastic and elastic scattering mechanisms, we consider another interaction possibility: this time an inelastic interaction. Given enough energy, neutrinos can excite the struck nucleon to an excited state. In this case, the neutrino interaction produces a baryon resonance (\( N^* \)). The baryon resonance quickly decays, most often to a nucleon and single pion final state

\[ \nu \mu N \rightarrow \mu^- N^*, \]

\[ N^* \rightarrow \pi N', \]

where \( N, N' = n, p \). Other higher multiplicity decay modes are also possible and will be discussed later.

The most common means of single pion production in intermediate energy neutrino scattering arises through this mechanism. In scattering off of free nucleons, there are seven possible resonant single pion reaction channels (seven each for neutrino and antineutrino scattering), three charged current:

\[ \nu \mu p \rightarrow \mu^- p \pi^+, \quad \bar{\nu} \mu p \rightarrow \mu^+ p \pi^-, \]

\[ \nu \mu n \rightarrow \mu^- n \pi^0, \quad \bar{\nu} \mu p \rightarrow \mu^+ n \pi^0, \]

\[ \nu \mu n \rightarrow \mu^- n \pi^+, \quad \bar{\nu} \mu n \rightarrow \mu^+ n \pi^-, \]

and four neutral current:

\[ \nu \mu p \rightarrow \nu \mu p \pi^0, \quad \bar{\nu} \mu p \rightarrow \bar{\nu} \mu p \pi^0, \]

\[ \nu \mu n \rightarrow \nu \mu n \pi^+, \quad \bar{\nu} \mu n \rightarrow \bar{\nu} \mu n \pi^0, \]

\[ \nu \mu n \rightarrow \nu \mu p \pi^-, \quad \bar{\nu} \mu n \rightarrow \bar{\nu} \mu p \pi^- . \]
To describe such resonance production processes, neutrino experiments most commonly use calculations from the Rein and Sehgal model (Feynman, Kislinger, and Ravndal, 1971; Rein and Sehgal, 1981; Rein, 1987) with the additional inclusion of lepton mass terms. This model gives predictions for both CC and NC resonance production and a prescription for handling interferences between overlapping resonances. The cross sections for the production of numerous different resonances are typically evaluated, though at the lowest energies the process is dominated by production of the Δ(1232).

Figures 13–15 summarize the historical measurements of CC neutrino single pion production cross sections as a function of neutrino energy. Table X lists corresponding measurements in antineutrino scattering. Many of these measurements were conducted on light (hydrogen or deuterium) targets and served as a crucial verification of cross section predictions at the time. Measurements of the axial mass were often repeated using these samples. Experiments also performed tests of resonance production models by measuring invariant mass and angular distributions. However, many of these tests were often limited in statistics.

Compared to their charged current counterparts, measurements of neutral-current single pion cross sections tend to be much more sparse. Most of these data exist in the form of NC and CC cross section ratios (Table XI); however, a limited number of absolute cross section measurements were also performed over the years (Figs. 16–21).

Today, improved measurements and predictions of neutrino-induced single pion production have become increasingly important because of the role such processes play in the interpretation of neutrino oscillation data (Walter, 2007). In this case, both NC and CC processes contribute. NC π⁰ production is often the largest νµ-induced background in experiments searching for νµ → νe oscillations. In addition, CC π⁰ production processes can present a non-negligible complication in the determination of neutrino energy in experiments measuring parameters associated with νµ and ¯νµ disappearance. Since such neutrino oscillation experiments use heavy materials as their neutrino

---

**TABLE X.** Measurements of antineutrino CC single pion production from BEBC (Allasia et al., 1983; Allen et al., 1986; Jones et al., 1989), FNAL (Barish et al., 1980), Gargamelle (Bolognese et al., 1979), and Sepukhov heavy liquid chamber (SKAT) (Grabosch et al., 1989).

| Channel | Experiment | Target | No. Events |
|---------|------------|--------|------------|
| ν̅μp → μ⁺pπ⁰: | BEBC | D₂ | 300 |
| | BEBC | H₂ | 609 |
| | GGM | CF₃Br | 282 |
| | FNAL | H₂ | 175 |
| | SKAT | CF₃Br | 145 |
| ν̅μn → μ⁺nπ⁰: | GGM | CF₃Br | 179 |
| | SKAT | CF₃Br | 83 |
| ν̅μn → μ⁺nπ⁻: | BEBC | D₂ | 545 |
| | GGM | CF₃Br | 266 |
| | SKAT | CF₃Br | 178 |

---

**FIG. 13.** Existing measurements of the cross section for the CC process, ν̅μp → μ⁻pπ⁺, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming Mₐ = 1.1 GeV. Modern measurements (Table XII) exist but cannot be directly compared with this historical data.

**FIG. 14.** Existing measurements of the cross section for the CC process, ν̅μn → μ⁻pπ⁺, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming Mₐ = 1.1 GeV. Modern measurements (Table XII) exist but cannot be directly compared with this historical data.

**FIG. 15.** Existing measurements of the cross section for the CC process, ν̅μn → μ⁻nπ⁺, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming Mₐ = 1.1 GeV. Modern measurements (Table XII) exist but cannot be directly compared with this historical data.
targets, measuring and modeling nuclear effects in pion production processes has become paramount. Such effects are sizable, not well known, and ultimately complicate the description of neutrino interactions. Once created in the initial neutrino interaction, the pion must escape the nucleus before it can be detected. Along its journey, the pion can rescatter, get absorbed, or charge exchange thus altering its description of neutrino interactions. Once created in the form of both ratios and absolute cross sections, pion production cross section reportings. Measurements have been produced in the form of both ratios and absolute cross sections, all on carbon-based targets. Similar measurements on additional nuclear targets are clearly needed to help round out our understanding of nuclear effects in pion production interactions.

Before we move on, it should be noted that many of the same baryon resonances that decay to single pion final states can also decay to photons (e.g., $\Delta \rightarrow N\gamma$ and $N^* \rightarrow N\gamma$). Such radiative decay processes have small branching fractions (<1%) yet, like NC $\pi^0$ production, they still pose non-negligible sources of background to $\nu_\mu \rightarrow \nu_e$ oscillation searches. There have been no direct experimental measurements of neutrino-induced resonance radiative decay to date; however, studies of photon production in deep inelastic neutrino interactions have been performed at higher energies.

Modern experiments have realized the importance of final-state effects, often directly reporting the distributions of final-state particles they observe. Such “observable” cross sections are more useful in that they measure the combined effects of nuclear processes and are much less model dependent. Table XII lists the collection of some of these most recent pion production cross section reportings. Measurements have been produced in the form of both ratios and absolute cross sections, all on carbon-based targets. Similar measurements on additional nuclear targets are clearly needed to help round out our understanding of nuclear effects in pion production interactions.

![FIG. 16. Existing measurements of the cross section for the NC process, $\nu_\mu p \rightarrow \nu_\mu p\pi^0$, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming $M_\pi = 1.1$ GeV. The Gargamelle measurement comes from a more recent reanalysis of these data. Modern measurements (Table XII) exist but cannot be directly compared with this historical data. From Hawker, 2002.](image)

![FIG. 17. Existing measurements of the cross section for the NC process, $\bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p\pi^0$, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming $M_\pi = 1.1$ GeV. Modern measurements (Table XII) exist but cannot be directly compared with this historical data.](image)
cannot be directly compared with this historical data. From Hawker, recently reported by the NOMAD collaboration (Kullenberg 2007; Efrosinin, Kudenko, and Khotjantsev, 2009; Jenkins 2007; Efrosinin, Kudenko, and Khotjantsev, 2009; Jenkins and Goldman, 2009; Hill, 2011; Ankowski et al., 2012).

In addition to photon decay, baryon resonances can also decay in a variety of other modes. This includes multipion and kaon final states which we return to later in this section.

(Ballagh et al., 1983). New experimental investigations are clearly needed. As an example, such a photon search was recently reported by the NOMAD collaboration (Kullenberg et al., 2012). New calculations have already begun to explore the possibility for standard model–based sources of photon production in neutrino scattering (Harvey, Hill, and Hill, 2007; Efrosinin, Kudenko, and Khotjantsev, 2009; Jenkins and Goldman, 2009; Hill, 2011; Ankowski et al., 2012).

In addition to photon decay, baryon resonances can also decay in a variety of other modes. This includes multipion and kaon final states which we return to later in this section.

**FIG. 18.** Existing measurements of the cross section for the NC process, $\nu_\mu n \rightarrow \nu_\mu n \pi^0$, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming $M_A = 1.1$ GeV. The Gargamelle measurement comes from a more recent reanalysis of these data. Modern measurements (Table XII) exist but cannot be directly compared with this historical data. From Hawker, 2002.

**FIG. 19.** Existing measurements of the cross section for the NC process, $\nu_\mu p \rightarrow \nu_\mu p \pi^+$, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming $M_A = 1.1$ GeV.

**FIG. 20.** Existing measurements of the cross section for the NC process, $\nu_\mu n \rightarrow \nu_\mu n \pi^0$, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming $M_A = 1.1$ GeV.

**FIG. 21.** Existing measurements of the cross section for the NC process, $\bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p \pi^-$, as a function of neutrino energy. Also shown is the prediction from Casper (2002) assuming $M_A = 1.1$ GeV.

**TABLE XII.** Current measurements of single pion production by neutrinos. In the last column, $\sigma$ refers to a measurement of the total flux-integrated cross section. Measurements are listed from K2K (Nakayama et al., 2005; Rodriguez et al., 2008; Mariani et al., 2011), MiniBooNE (Aguilar-Arevalo et al., 2009; 2010; 2011a; 2011b), and SciBooNE (Kurimoto et al., 2010a).

| Experiment       | Target | Process                  | Cross section measurements                  |
|------------------|--------|--------------------------|---------------------------------------------|
| K2K              | C_7H_8 | $\nu_\mu$ CC $\pi^+/\text{QE}$ | $\sigma$, $\sigma(E_\nu)$                   |
| K2K              | C_7H_8 | $\nu_\mu$ CC $\pi^0/\text{QE}$ | $\sigma$, $\sigma(E_\nu)$                   |
| K2K              | C_7H_8 | $\nu_\mu$ NC $\pi^0/\text{CC}$ | $\sigma$, $\sigma(E_\nu)$                   |
| MiniBooNE        | CH_2   | $\nu_\mu$ CC $\pi^+$    | $\sigma$, $\sigma(E_\nu)$                   |
| MiniBooNE        | CH_2   | $\nu_\mu$ CC $\pi^0$    | $\sigma$, $\sigma(E_\nu)$                   |
| MiniBooNE        | CH_2   | $\nu_\mu$ NC $\pi^0$    | $\sigma$, $\sigma(E_\nu)$                   |
| MiniBooNE        | CH_2   | $\nu_\mu$ NC $\pi^0$    | $\sigma$, $\sigma(E_\nu)$                   |
| MiniBooNE        | CH_2   | $\nu_\mu$ NC $\pi^0$    | $\sigma$, $\sigma(E_\nu)$                   |
| SciBooNE         | C_7H_8 | $\nu_\mu$ NC $\pi^0/\text{CC}$ | $\sigma$, $\sigma(E_\nu)$                   |
D. Coherent pion production

In addition to resonance production, neutrinos can also coherently produce single pion final states. In this case, the neutrino coherently scatters from the entire nucleus, transferring negligible energy to the target (A). These low-$Q^2$ interactions produce no nuclear recoil and a distinctly forward-scattered pion, compared to their resonance-mediated counterparts. Both NC and CC coherent pion production processes are possible,

\[ \nu \mu A \rightarrow \nu \mu A \pi^0, \quad \bar{\nu} \mu A \rightarrow \bar{\nu} \mu A \pi^0, \quad (77) \]

\[ \nu \mu A \rightarrow \mu^- A \pi^+, \quad \bar{\nu} \mu A \rightarrow \mu^+ A \pi^-. \quad (78) \]

While the cross sections for these processes are predicted to be comparatively small, coherent pion production has been observed across a broad energy range in both NC and CC interactions of neutrinos and antineutrinos. Figure 22 shows a collection of existing measurements of coherent pion production cross sections for a variety of nuclei. A valuable compilation of the same is also available in Vilain et al., 1993. Most of these historical measurements were performed at higher energies ($E_{\nu} > 2$ GeV). Table XIII provides a listing of more recent measurements of coherent pion production, most in the form of cross section ratios that were measured at low energy ($E_{\nu} < \sim 2$ GeV). Experiments measuring coherent pion production at these very low neutrino energies have typically observed less coherent pion production than predicted by models which well describe the high-energy data. In addition, the production of CC coherent pion events at low energy has been seemingly absent from much of the experimental data (Hasegawa et al., 2005; Hiraide et al., 2008), although refined searches have indicated some evidence for their existence (Hiraide, 2009).

To date, it has been a challenge to develop a single description that can successfully describe existing coherent pion production measurements across all energies. The most common theoretical approach for describing coherent pion production is typically based on Adler’s partially conserved axial current (PCAC) theorem (Adler, 1964) which relates neutrino-induced coherent pion production to pion-nucleus elastic scattering in the limit $Q^2 = 0$. A nuclear form factor is then invoked to extrapolate to nonzero values of $Q^2$. Such PCAC-based models (Rein and Sehgal, 1983) have existed for many years and have been rather successful in describing coherent pion production at high energy (the prediction shown in Fig. 22 is such a model). With the accumulation of increasingly large amounts of low-energy neutrino data, revised approaches have been applied to describe the reduced level of coherent pion production observed by low-energy experiments. Two such approaches have been developed. The first class of models are again based on PCAC (Rein and Sehgal, 1983; Belkov and Kopeliovich, 1987; Paschos and Kartavtsev, 2003; Kopeliovich, 2005; Paschos et al., 2006; Berger and Sehgal, 2009; Hernandez et al., 2009; Paschos et al., 2009). The other class is microscopic models involving a resonance production Kelkar et al., 1997), Singh et al., 2006, Alvarez-Ruso et al., 2007), Amaro et al., 2009, T. Leitner et al., 2009, Hernandez et al., 2010, Nakamura, S. X. et al., 2010, and Martini, Ericson, and Chanfray (2011). Because this latter class involves $A$ formation, their validity is limited to the low-energy region. An excellent review of the current experimental and theoretical situation is available in Alvarez-Ruso (2011a). The study and prediction of coherent pion production is important as it provides another source of potential background for neutrino oscillation experiments.

![FIG. 22. Measurements of absolute coherent pion production cross sections from a variety of nuclear targets and samples, as indicated in the legend. Both NC and CC data are displayed on the same plot after rescaling the CC data using the prediction that $\sigma_{NC} = \frac{1}{2} \sigma_{CC}$ (Rein and Sehgal, 1983). In addition, data from various targets have been corrected to carbon cross sections assuming $A^{1/3}$ scaling (Rein and Sehgal, 1983). Also shown is the prediction from Casper (2002).](image)

E. Multipion production

As mentioned, the baryonic resonances created in neutrino-nucleon interactions can potentially decay to multipion final states. Other inelastic processes, such as deep inelastic scattering, can also contribute a copious source

| Experiment | Target | $E_{\nu}$ | Measurement |
|------------|--------|----------|-------------|
| K2K        | C$_6$H$_8$ | 1.3 GeV | $\sigma(\text{CC coherent } \pi^+/\text{CC})$ |
| SciBooNE   | C$_6$H$_8$ | 1.1 GeV | $\sigma(\text{CC coherent } \pi^+/\text{CC})$ |
| SciBooNE   | C$_6$H$_8$ | 1.1, 2.2 GeV | $\sigma(\text{CC coherent } \pi^+/\text{NC coherent } \pi^0)$ |
| MiniBooNE  | CH$_2$ | 1.1 GeV | $\sigma(\text{NC coherent } \pi^+/\text{NC coherent } \pi^0)$ |
| NOMAD      | C-based | 24.8 GeV | $\sigma(\text{NC coherent } \pi^0)$ |
| SciBooNE   | C$_6$H$_8$ | 1.1 GeV | $\sigma(\text{NC coherent } \pi^0/\text{CC})$ |
of multipion final states depending on the neutrino energy. Figures 23–25 show existing measurements of neutrino-induced di-pion production cross sections compared to an example prediction including contributions from both resonant and deep inelastic scattering mechanisms. Because of the inherent complexity of reconstructing multiple pions final states, there are not many existing experimental measurements of this process. All of the existing measurements have been performed strictly using deuterium-filled bubble chambers. Improved measurements will be important because they test our understanding of the transition region and will provide a constraint on potential backgrounds for neutrino oscillation experiments operating in higher energy beams.

F. Kaon production

Neutrino interactions in this energy range can also produce final states involving strange quarks. Some of the contributing strange production channels at intermediate energies include the following processes:

\[
\begin{align*}
\text{CC:} & \quad \nu_\mu n \rightarrow \mu^- K^+ \Lambda^0 \\
\text{NC:} & \quad \nu_\mu p \rightarrow \nu_\mu K^+ \Lambda^0 \\
& \quad \nu_\mu p \rightarrow \mu^- K^+ p \\
& \quad \nu_\mu n \rightarrow \nu_\mu K^0 \Lambda^0 \\
& \quad \nu_\mu n \rightarrow \mu^- K^0 \Lambda^0 \\
& \quad \nu_\mu p \rightarrow \nu_\mu K^+ \Sigma^0 \\
& \quad \nu_\mu n \rightarrow \nu_\mu K^0 \Sigma^0 \\
& \quad \nu_\mu n \rightarrow \mu^- K^0 \Sigma^0 \\
& \quad \nu_\mu n \rightarrow \nu_\mu K^- \Sigma^+ \\
& \quad \nu_\mu n \rightarrow \nu_\mu K^+ \Sigma^- \\
& \quad \nu_\mu n \rightarrow \mu^- K^- \Sigma^+ .
\end{align*}
\]

(79)

These reactions typically have small cross sections due in part to the kaon mass and because the kaon channels are not enhanced by any dominant resonance. Measuring neutrino-induced kaon production is of interest primarily as a source of potential background for proton decay searches. Proton decay modes containing a final-state kaon, \( p \rightarrow K^+ \bar{\nu} \), have large branching ratios in many supersymmetry grand unified theory models. Because there is a nonzero probability that an atmospheric neutrino interaction can mimic such a proton decay signature, estimating these background rates has become an increasingly important component to such searches.

Figure 26 shows the only two experiments which have published cross sections on the dominant associated production channel, \( \nu_\mu n \rightarrow \mu^- K^+ \Lambda^0 \). Both bubble chamber measurements were performed on a deuterium target and are based on less than 30 events combined. Many other measurements of strange particle production yields have been performed throughout the years, most using bubble chambers (Barish et al., 1974; Deden et al., 1975; Berge et al., 1976, 1978; Blietschau et al., 1976; Bell et al., 1978; Hasert et al., 1978; Krenz et al., 1978b; Baker et al., 1981, 1986; Bosetti et al., 1982; Brock et al., 1982; Grassler et al., 1982; Son et al., 1983; Aderholz et al., 1992; Willoqu et al., 1992; Jones et al., 1993; DeProspo et al., 1994; Agababyan et al., 2006). More recently, NOMAD has reported NC and CC strange particle production yields and multiplicities for a variety of reaction kinematics (Astier et al., 2002; Naumov et al., 2004; Chukanov et al., 2006).
As far as theoretical calculations go, predictions for these neutrino-induced kaon production processes have existed for several decades (Albright, 1975; Ezawa et al., 1975; Shrock, 1975; Amer, 1978; Dewan, 1981), although there have been several revised calculations in recent years (Ader et al., 2010; Alam et al., 2010, 2012).

G. Outlook

In summary, neutrino scattering at intermediate energies is notoriously complex and the level to which these contributing processes have been studied remains incomplete (Benhar, 2010; Alvarez-Ruso, 2011b). Improved experimental measurements and theoretical calculations will be especially important for reducing systematics in future precision neutrino oscillation experiments. Luckily, such studies are already underway making use of new intense accelerator-based sources of neutrinos. However, for such updated cross section measurements to be robust, they must be accompanied by an equally precise knowledge of the incoming neutrino flux. Improved hadro-production measurements are key to providing the level of precision necessary. In addition, further scrutiny of nuclear effects in intermediate energy neutrino and antineutrino interactions is absolutely essential. Analysis of data from the MINERνA experiment will soon enable the first detailed look at nuclear effects in neutrino interactions. Together, theoretical advances and new data taken on a variety of nuclear targets from the ArgoNeuT, K2K, MicroBooNE, MINERνA, MiniBooNE, MINOS, NOMAD, NOVA, and SciBooNE experiments should provide both a necessary and broad foundation going into the future. In order to make progress in our understanding of this energy regime and provide the most clarity, experiments should strive to report what they directly detect in the final state, for example, in the form of model-independent differential cross sections.

VI. HIGH-ENERGY CROSS SECTIONS: $E_\nu \sim 20\text{–}500\text{ GeV}$

Up to now, we have largely discussed neutrino scattering from composite entities such as nucleons or nuclei. Given enough energy, the neutrino can actually begin to resolve the internal structure of the target. In the most common high-energy interaction, the neutrino can scatter off an individual quark inside the nucleon, a process called deep inelastic scattering (DIS). An excellent review of this subject has been previously published in this journal (Conrad, Shaevitz, and Bolton, 1998), therefore we provide only a brief summary of the DIS cross section, relevant kinematics, and most recent experimental measurements here.

A. Deep inelastic scattering

Neutrino deep inelastic scattering has long been used to validate the standard model and probe nucleon structure. Over the years, experiments have measured cross sections, electroweak parameters, coupling constants, nucleon structure functions, and scaling variables using such processes. In deep inelastic scattering (Fig. 27), the neutrino scatters off a quark in the nucleon via the exchange of a virtual $W$ or $Z$ boson producing a lepton and a hadronic system in the final state. Both CC and NC processes are possible

\begin{align}
\nu_\mu N &\rightarrow \mu^- X, \quad \bar{\nu}_\mu N \rightarrow \mu^+ X, \\
\nu_\tau N &\rightarrow \nu_\tau X, \quad \bar{\nu}_\tau N \rightarrow \bar{\nu}_\tau X.
\end{align}

Here we restrict ourselves to the case of $\nu_\mu$ scattering, as an example, though $\nu_e$ and $\nu_\tau$ DIS interactions are also possible.

Following the formalism introduced in Sec. II, DIS processes can be completely described in terms of three dimensionless kinematic invariants. The first two, the inelasticity ($y$) and the four-momentum transfer ($Q^2 = -q^2$), have already been defined. We now define the Bjorken scaling variable $x$.

\begin{equation}
x = \frac{Q^2}{2p_e \cdot q} \quad \text{(Bjorken scaling variable).}
\end{equation}

The Bjorken scaling variable plays a prominent role in deep inelastic neutrino scattering, where the target can carry a portion of the incoming energy momentum of the struck nucleus.

\begin{figure}
\centering
\includegraphics[width=0.7\textwidth]{fig27}
\caption{Feynman diagram for a CC neutrino DIS process. In the case of NC DIS, the outgoing lepton is instead a neutrino and the exchange particle is a $Z$ boson. From Conrad, Shaevitz, and Bolton, 1998.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.7\textwidth]{fig26}
\caption{Measurements of the associated production cross section, $\nu_\mu n \rightarrow \mu^- K^+ A^0$, as a function of neutrino energy. Also shown is the prediction from Casper (2002) which includes both resonant and DIS contributions.}
\end{figure
On a practical level, these Lorentz-invariant parameters cannot be readily determined from four-vectors, but they can be reconstructed using readily measured observables in a given experiment,

\[ x = \frac{Q^2}{2M_{\nu}} = \frac{Q^2}{2ME_{\nu}}, \]

\[ y = E_{\text{had}}/E_{\nu}, \]

\[ Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - p_\mu \cos \theta_\mu), \]

where \( E_\nu \) is the incident neutrino energy, \( M_N \) is the nucleon mass, \( \nu = E_{\text{had}} \) is the energy of the hadronic system, and \( E_\mu \), \( p_\mu \), and \( \cos \theta_\mu \) are the energy, momentum, and scattering angle of the outgoing muon in the laboratory frame. In the case of NC scattering, the outgoing neutrino is not reconstructed. Thus, experimentally, all of the event information must be inferred from the hadronic shower in that case.

Using these variables, the inclusive cross section for DIS scattering of neutrinos and antineutrinos can be written as

\[ \frac{d^2 \sigma^{\nu, \bar{\nu}}}{dx dy} = \frac{G_F^2 M_\nu}{\pi(1 + Q^2/M_{W,2}^2)} \left[ y^2 \frac{2y}{2} F_1(x, Q^2) + \left(1 - y - \frac{M_{W,2} y}{2E}\right) F_2(x, Q^2) \right] \]

\[ \pm y \left(1 - y\right) x F_3(x, Q^2) \]

(86)

where \( G_F \) is again the Fermi weak coupling constant, \( M_{W,2} \) is the mass of the \( W^- \) (\( Z^0 \) boson) in the case of CC (NC) scattering, and the \( (+/-) \) sign in the last term refers to neutrino (antineutrino) interactions. In Eq. (86), \( F_i(x, Q^2) \) are the dimensionless nucleon structure functions that encompass the underlying structure of the target. For electron scattering, there are two structure functions while for neutrino scattering there is additionally a third structure function, \( x F_3(x, Q^2) \), which represents the V.A interference term.

Assuming the quark parton model, in which the nucleon consists of partons (quarks and gluons), \( F_i(x, Q^2) \) can be expressed in terms of the quark composition of the target. They depend on the target and type of scattering interaction and are functions of \( x \) and \( Q^2 \). In the simplest case, the nucleon structure functions can then be expressed as the sum of the probabilities,

\[ F_2(x, Q^2) = 2 \sum_{i=u,d,...} [x q(x, Q^2) + x \bar{q}(x, Q^2)] \]

(87)

\[ x F_3(x, Q^2) = 2 \sum_{i=u,d,...} [x q(x, Q^2) - x \bar{q}(x, Q^2)] \]

(88)

where the sum is over all quark species. The struck quark carries a fraction \( x \) of the nucleon’s momentum, such that \( x q(x, Q) \) is the probability of finding the quark (antiquark) with a given momentum fraction. These probabilities are known as parton distribution functions (PDFs). In this way, \( F_2(x, Q^2) \) measures the sum of the quark and antiquark PDFs in the nucleon, while \( x F_3(x, Q^2) \) measures their difference and is therefore sensitive to the valence quark PDFs. The third structure function \( 2x F_1(x, Q^2) \) is commonly related to \( F_3(x, Q^2) \) via a longitudinal structure function, \( R_L(x, Q^2) \),

\[ F_3(x, Q^2) = 1 + R_L(x, Q^2) \frac{1 + 4M^2x^2/Q^2}{1 + 4M^2x/Q^2} 2x F_1(x, Q^2), \]

(89)

where \( R_L(x, Q^2) \) is the ratio of cross sections for scattering off longitudinally and transversely polarized exchange bosons.

Measurement of these structure functions has been the focus of many charged lepton and neutrino DIS experiments, which together have probed \( F_2(x, Q^2), R_L(x, Q^2), \) and \( x F_3 \) (in the case of neutrino scattering) over a wide range of \( x \) and \( Q^2 \) values (Nakamura, K. et al., 2010). Neutrino scattering is unique, however, in that it measures the valence quark distributions through measurement of \( x F_3 \) and the strange quark distribution through detection of neutrino-induced dimuon production. These provide important constraints that cannot be obtained from either electron or muon scattering experiments.

While Eq. (86) provides a tidy picture of neutrino DIS, additional effects must be included in any realistic description of these processes. The inclusion of lepton masses (Albright and Jarlskog, 1975; Kretzer and Reno, 2002), higher order QCD processes (Moch and Vermaseren, 2000; McFarland and Moch, 2003; Dobrescu and Ellis, 2004), nuclear effects, radiative corrections (Sirlin and Marciano, 1981; Arbuzov et al., 2005; De Rujula, Petronzio, and Savoy-Navarro, 1979; Bardin and Dokuchaeva, 1980; Diener et al., 2004), target mass effects (Schienbein et al., 2008), heavy quark production (Barnett, 1976; Georgi and Politzer, 1976; Gottschalk, 1981), and nonperturbative higher twist effects (Buras, 1980) further modify the scattering kinematics and cross sections. In general, these contributions are typically well known and do not add large uncertainties to the predicted cross sections.

Having completed a brief description of DIS, we next turn to some of the experimental measurements. Table XIV lists the most recent experiments that have probed such high-energy neutrino scattering. To isolate DIS events, neutrino experiments typically apply kinematic cuts to remove quasielastic scattering (Sec. V.A) and resonance-mediated (Sec. V.C) contributions from their data. Using high statistics samples of DIS events, these experiments have provided measurements of the weak mixing angle \( \sin^2\theta_W \) from NC

| Experiment | Target | \( E_\nu \) (GeV) | Statistics | Year | Results |
|------------|--------|----------------|------------|------|---------|
| CHORUS     | Pb     | 10–200         | 8.7 \times 10^7 \nu, 1.5 \times 10^5 \bar{\nu} | 1995–1998 | \( F_2(x, Q^2) \), \( x F_3(x, Q^2) \) |
| MINOS      | Fe     | 3–50           | 19.4 \times 10^4 \nu, 1.6 \times 10^5 \bar{\nu} | 2005–present | \( \sigma(E_\nu) \) |
| NOMAD      | C      | 3–300          | 10.4 \times 10^4 \nu | 1995–1998 | \( \sigma(E_\nu) \) |
| NuTeV      | Fe     | 30–360         | 8.6 \times 10^3 \nu, 2.3 \times 10^5 \bar{\nu} | 1996–1997 | \( F_2(x, Q^2) \), \( x F_3(x, Q^2) \), \( \sigma(E_\nu) \), \( \frac{d^2 \sigma}{dx dy} \), \( \sin^2\theta_W \) |
Indicate the world-averaged cross sections, refers to an isoscalar nucleon within the target. The dotted lines energies, see the complete compilation in Fig. 9. (Nakamura, K. 1983) and CERN Hybrid Oscillation Research apparatus in nuclear emulsion detectors such as E531 (Ushida et al. 1982), CHARM-II (Vilain et al., 1987), Harvard-Penn-Wisconsin-Fermilab (HPWF) (Aubert et al., 1974; Benvenuti et al., 1978), NOMAD (Astier et al., 2000), and NuTeV (Goncharov et al., 2001; Mason et al., 2007b), in bubble chambers like Big European Bubble Chamber (BEBC) (Gerbier, 1985), Fermi National Accelerator Laboratory (FNAL) (Ballagh et al., 1981; Baker et al., 1985) and Gargamelle (Haauft et al., 1983) as well as in nuclear emulsion detectors such as E531 (Ushida et al., 1983) and CERN Hybrid Oscillation Research apparatus (CHORUS) (Onengut et al., 2004; Kayis-Topaksu et al., 2005, 2008b, 2011; Onengut et al., 2005). This latter class of measurements is particularly important for constraining the strange and antistrange quark content of the nucleon and their momentum dependence.

In the near future, high statistics measurements of neutrino and antineutrino DIS are expected from the MINERνA experiment (Drakoulakos et al., 2004). With multiple nuclear targets, MINERνA will also be able to complete the first detailed examination of nuclear effects in neutrino DIS.

VII. ULTRA-HIGH-ENERGY NEUTRINOS: 0.5 TEV–1 EEV

In reaching the ultra-high-energy scale, we find ourselves, remarkably, back to the beginning of our journey at extremely low energies. Neutrinos at this energy scale have yet to manifest themselves as confirmed observations, though our present technology is remarkably close to dispelling that fact. To date, the highest energy neutrino recorded is several hundred TeV (DeYoung, 2011). However, experimentalists and theorists have their aspirations set much higher, to energies above 10^{15} eV. On the theoretical side, this opens the door for what could be called “neutrino astrophysics.” A variety of astrophysical objects and mechanisms become accessible at these energies, providing information that is complementary to that already obtained from electromagnetic or hadronic observations.

In response to the call, the experimental community has forged ahead with a number of observational programs and techniques geared toward the observation of ultra-high-energy neutrinos from astrophysical sources. The range of these techniques include detectors scanning for ultra-high-energy cosmic neutrino-induced events in large volumes of water [Baikal (Antipin et al., 2007; Aynutdinov et al., 2009), Antares (Aslanides et al., 1999)], ice [Antarctic Muon And Neutrino Detector Array (AMANDA) (Achterberg et al., 2007), IceCube (de los Heros, 2011), Radio Ice Cerenkov Experiment (RICE) (Kravchenko et al., 2003), Fast On-orbit Recording of Transient Events (FORTE) (Lehtinen et al., 2004), ANITA (Barwick et al., 2006)], the Earth’s atmosphere [Pierre Auger (Abraham et al., 2008), HiRes (Abbasi et al., 2004)], and the lunar regolith [Goldstone Lunar Ultra-High Energy experiment (GLUE) (Gorham et al., 2004)]. Even more future programs are in the planning stages. As such, the knowledge of neutrino cross section in this high-energy region is becoming ever increasing in importance. Once first detection is firmly established, the emphasis is likely to shift toward obtaining more detailed information about the observed astrophysical objects, and thus the neutrino fluxes will need to be examined in much greater detail.

The neutrino cross sections in this energy range^{12} are essentially extensions of the high-energy parton model discussed in Sec. VI. However, at these energies, the propagation term from the interaction vertex is no longer dominated by the W-Z boson mass. As a result, the cross section no longer grows linearly with neutrino energy. The propagator term in fact suppresses the cross sections for energies above 10 TeV. Likewise, the \((1 - y)^2\) suppression that typically allows distinction between neutrino and antineutrino interactions is much less pronounced, making the two cross sections \((νN)\) and \(\bar{ν}N\) nearly identical.

For a rough estimate of the neutrino cross section at these high energies \((10^{16} \lesssim E_\nu \lesssim 10^{21} \text{ eV})\), the following power

\[E_\nu^{-\lambda} \lesssim 10^{21} \text{ eV}\],

\[E_\nu^{-\lambda} \lesssim 10^{21} \text{ eV}\].
law dependence provides a reasonable approximation (Gandhi et al., 1996):
\[
\sigma_{\nu N}^{CC} = 5.53 \times 10^{-36} \text{ cm}^2 \left( \frac{E_\nu}{1 \text{ GeV}} \right)^\alpha,
\]
(90)
\[
\sigma_{\nu N}^{NC} = 2.31 \times 10^{-36} \text{ cm}^2 \left( \frac{E_\nu}{1 \text{ GeV}} \right)^\alpha,
\]
(91)
where \( \alpha \approx 0.363 \).

There is one peculiar oddity that is worth highlighting for neutrino cross sections at such high energies. Neutrino-electron scattering is usually subdominant to any neutrino-nucleon interaction because of its small target mass. There is one notable exception, however when the neutrino undergoes a resonant enhancement from the formation of an intermediate \( W \) boson in \( \nu_e e^- \) interactions. This resonance formation takes place at \( E_{\nu e} = M_W^2 / 2m_e = 6.3 \text{ PeV} \) and is by far more prominent than any \( \nu N \) interaction up to \( 10^{21} \text{ eV} \) (see Fig. 29). The mechanism was first suggested by Glashow in 1960 as a means to directly detect the \( W \) boson (Glashow, 1960). The cross section was later generalized by Berezinsky and Gazizov (1977) to other possible channels:

\[
\frac{d\sigma(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-)}{dy} = \frac{2G^2_F m_\nu E_\nu}{\pi} \left[ \frac{g^2_L}{(1 + 2m_\nu E_\nu / M_W^2)^2} + \frac{1}{1 + 2m_\nu E_\nu / M_W^2 + i\Gamma_W / M_W} \right],
\]
(92)

and depart substantially from standard model predictions if new physics is present (Gandhi et al., 1996).

A. Uncertainties and projections

For a more accurate prediction of the cross section, a well-formulated model of the relevant quark structure functions is needed. This predictive power is especially important in the search for new physics. At such high energies, the neutrino cross section can depart substantially from the standard model prediction if new physics is at play. Study of such high-energy neutrinos can be a possible probe into new physics.

Direct neutrino scattering measurements at such extreme energies are, of course, unavailable. Therefore, predictions rely heavily on the existing knowledge of parton distribution functions and, as the reader can imagine, extrapolation can introduce substantial uncertainties to these predictions. The best constraints on the relevant parton distribution functions stem from data collected from high-energy \( ep \) scattering experiments such as Hadron-Electron Ring Accelerator (HERA) (Chekanov et al., 2003). The challenge rests on the ability to fit existing data to as low values of \( x \) as possible. At high energies, the propagator term limits the maximum \( Q^2 \) to the \( M_{W,Z} \) mass. The relevant range for \( x \) then falls inversely with neutrino energy,

\[
x \sim \frac{M_W}{E_\nu}
\]
(93)

which, for EeV scales, implies \( x \) down to \( 10^{-8} \) or lower. The ZEUS Collaboration has recently extended their analysis of parton distribution function data down to \( x \approx 10^{-5} \), allowing a more robust extrapolation of the neutrino cross section to higher energies (Cooper-Sarkar and Sarkar, 2008). Uncertainties in their parton distribution function translate into \( \pm 4\% \) uncertainties for the neutrino cross section for center-of-mass energy of \( 10^4 \text{ GeV} \) and \( \pm 14\% \) uncertainties at \( \sqrt{s} = 10^6 \text{ GeV} \).

An equal factor in the precise evaluation of these cross sections is the selection of an adequate PDF itself. The conventional PDF makes use of the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi formalism (Altarelli and Parisi, 1977; Dokshitzer, 1977), which is a next-to-leading order

FIG. 29 (color online). Neutrino electron and nucleon scattering in the ultra-high-energy regime \( (E_\nu \geq 10^6 \text{ GeV}) \). Shown are the electron interactions \( \bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \) (crosses), \( \nu_e e^- \rightarrow \nu_e e^- \) (diamonds), \( \bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \) (hollow circles), \( \nu_e e^- \rightarrow \nu_e e^- \) (filled circles), and the nucleon charged current (cross markers) and neutral-current (filled triangles) interactions. The leptonic \( W \) resonance channel is clearly evident (Butkevich et al., 1988; Gandhi et al., 1996).
QCD calculation. As one pushes further down in $x$, the PDFs introduce greater uncertainties, whereby other approaches can be used, such as the formalism adopted by the Balitsky-Fadin-Kuraev-Lipatov group (Kuraev, Lipatov, and Padin, 1977; Ciafaloni et al., 2006). In reality, the approaches of both Dokshitzer-Gribov-Lipatov-Altarelli-Parisi and Balitsky-Fadin-Kuraev-Lipatov need to be combined in order to properly account for the $Q^2$ and $x$ evolution of these PDFs.

One of the more difficult effects to account for in these parametrization schemes is that of gluon recombination ($g g \to g$). Such a saturation must take place at the very highest energies in order to preserve unitarity. Groups have made use of nonlinear color glass condensate models as a way to model these effects (Iancu and Venugopalan, 2003). Such techniques have been successfully applied to Relativistic Heavy Ion Collider (RHIC) data (Jalilian-Marian and Kovchegov, 2006).

VIII. SUMMARY

In this work, we presented a comprehensive review of neutrino interaction cross sections. Our discussion ranged from eV to EeV energy scales and therefore spanned a broad range of underlying physics processes, theoretical calculations, and experimental measurements.

While our knowledge of neutrino scattering may not be equally precise at all energies, one cannot help but marvel at how far our theoretical frameworks extend. From literally zero-point energy to unfathomable reaches, it appears that our models can shed some light in the darkness. Equally remarkable is the effort by which we seek to ground our theories. Where data do not exist, we seek other anchors by which we can assess their validity. When even that approach fails, we pile model against model in the hopes of finding weaknesses that ultimately will strengthen our foundations.

As the journey continues into the current millennium, we find that more and more direct data are being collected to guide our theoretical understanding. Currently, new experiments are coming online to shed more light on neutrino interactions. Therefore, we believe that, as comprehensive as we have tried to make this review, it is certainly an incomplete story whose chapters continue to be written.

ACKNOWLEDGMENTS

The authors thank S. Brice, S. Dytman, D. Naples, J. P. Krane, G. Mention, and R. Tayloe for help in gathering experimental data used in this review. The authors also thank W. Haxton, W. Donnelly, and R. G. H. Robertson for their comments and suggestions pertaining to this work. J. A. Formaggio is supported by the United States Department of Energy under Grant No. DE-FG02-06ER-41420. G. P. Zeller is supported via the Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

REFERENCES

Abbasi, R. U., et al. (High Resolution Flys Eye Collaboration), 2004, Phys. Rev. Lett. 92, 151101.
Sirlin, A., and W. Marciano, 1981, Nucl. Phys. B189, 442.
Smith, R. A., and E. J. Moniz, 1972, Nucl. Phys. B43, 605.
Sobczyk, J. T., 2011, AIP Conf. Proc. 1405, 59.
Sobczyk, J. T., 2012, arXiv:1109.1081.
Son, D., et al., 1983, Phys. Rev. D 28, 2129.
Taddeucci, T. N., C. A. Goulding, T. A. Carey, R. C. Byrd, C. D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, and E. Sugarbaker, 1987, Nucl. Phys. A469, 125.
Tatara, N., Y. Kohyama, and K. Kubodera, 1990, Phys. Rev. C 42, 1694.
't Hooft, G., 1971, Phys. Lett. B 37, 195.
Towner, I. S., 1998, Phys. Rev. C 58, 1288.
Tzanov, M., et al., 2006a, Phys. Rev. D 74, 012008.
Ushida, N., et al. (Canada-Japan-Korea-USA Hybrid Emulsion Spectrometer Collaboration), 1983, Phys. Lett. 121B, 292.
Vershinsky, A. G., et al., 1991, JETP Lett. 53, 513.
Vidyakin, G. S., et al., 1987, JETP 93, 424.
Vilain, P., et al., 1993, Phys. Lett. B 313, 267.
Vilain, P., et al. (CHARM II Collaboration), 1999, Eur. Phys. J. C 11, 19.
Vilain, P., et al. (CHARM-II Collaboration), 1995a, Phys. Lett. B 364, 121.
Vilain, P., et al. (CHARM-II Collaboration), 1995b, Phys. Lett. B 345, 115.
Volpe, C., N. Auerbach, G. Colò, T. Suzuki, and N. Van Giai, 2000, Phys. Rev. C 62, 015501.
Walter, C., 2007, AIP Conf. Proc. 967, 3.
Watson, J. W., W. Pairsuwan, B. D. Anderson, A. R. Baldwin, B. S. Flanders, R. Madey, R. J. McCarthy, B. A. Brown, B. H. Wildenthal, and C. C. Foster, 1985, Phys. Rev. Lett. 55, 1369.
Webber, D. M., et al. (MuLan), 2011, Phys. Rev. Lett. 106, 041803.
Weinberg, S., 1962, Phys. Rev. 128, 1457.
Weinberg, S., 1967, Phys. Rev. Lett. 19, 1264.
Willis, S. E., et al., 1980, Phys. Rev. Lett. 44, 522.
Willocq, S., et al., 1992, Z. Phys. C 53, 207.
Wolfenstein, L., 1978, Phys. Rev. D 17, 2369.
Wu, Q., et al., 2008, Phys. Rev. B 660, 19.
Zacek, G., et al., 1986, Phys. Rev. D 34, 2621.
Zeitnitz, B., et al., 1994, Prog. Part. Nucl. Phys. 32, 351.
Zeller, G. P., et al., 2002, Phys. Rev. Lett. 88, 091802.