52. Neutrino Cross Section Measurements

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Neutrino cross sections are an essential ingredient in all neutrino experiments. Interest in neutrino scattering has increased due to the need for such information in the interpretation of neutrino oscillation data [1,2] and given that uncertainties in neutrino-nucleus scattering remain a dominate source of systematic uncertainty in many neutrino oscillation measurements. Historically, neutrino scattering results on both charged current (CC) and neutral current (NC) channels have been collected over many decades using a variety of targets, analysis techniques, and detector technologies. With the advent of intense neutrino sources constructed for neutrino oscillation investigations, experiments are now remeasuring such interaction cross sections with a renewed appreciation for nuclear effects[1] and the need for more precise neutrino flux estimations [3, 4]. This work summarizes accelerator-based neutrino cross section measurements performed in the $\sim 0.1-300$ GeV range with an emphasis on inclusive, quasi-elastic, and pion production processes, areas where we have the most experimental input at present (Table 52.1). For a more comprehensive discussion of neutrino cross sections, including neutrino-electron elastic scattering and lower energy neutrino measurements, the reader is directed to a review of this subject [5]. Here, we survey existing experimental data on neutrino interactions and do not attempt to provide a census of the associated theoretical calculations [6], which are both critical and plentiful. Companion electron-nucleus scattering data [7] are additionally playing an increased role in neutrino interaction predictions through such efforts as the e4ν collaboration [8].

Table 52.1: List of beam properties, targets, and run durations for modern accelerator-based neutrino experiments studying neutrino scattering.

Experiment	beam	$\langle E_\nu \rangle$, $\langle E_{\overline{\nu}} \rangle$ (GeV)	neutrino target(s)	run period
ArgoNeuT	$\nu,\overline{\nu}$	4.3, 3.6	Ar	2009 – 2010
FASERν	$\nu,\overline{\nu}$	> 200	W, emulsion	2021 –
ICARUS (at CNGS)	ν	20	Ar	2010 – 2012
ICARUS (at FNAL)	ν	0.8	Ar	2021 –
K2K	ν	1.3	CH, H_2O	2003 – 2004
MicroBooNE	ν	0.8	Ar	2015 – 2020
MINERvA	$\nu,\overline{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H_2O, Fe, Pb	2009 – 2019
MiniBooNE	$\nu,\overline{\nu}$	0.8, 0.7	CH_2	2002 – 2019
MINOS	$\nu,\overline{\nu}$	3.5, 6.1	Fe	2004 – 2016
NINJA	ν, $\overline{\nu}$	0.6, 0.6	Fe, emulsion	2015 –
NOMAD	$\nu,\overline{\nu}$	23.4, 19.7	C	1995 – 1998
NOvA	$\nu,\overline{\nu}$	2.0, 2.0	CH_2	2010 –
SBND	ν	0.8	Ar	2024 –
SciBooNE	$\nu,\overline{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	ν, $\overline{\nu}$	0.6, 0.6	CH, H_2O, Fe	2010 –

[1]Nuclear effects refer to kinematic and final state effects which impact neutrino scattering off nuclei. Such effects can be significant and are particularly relevant given that modern neutrino experiments make use of nuclear targets to increase their event yields.

52.1 Inclusive Scattering

Over the years, many experiments have measured the total inclusive charged current cross section for neutrino ($\nu_\mu N \to \mu^- X$) and antineutrino ($\overline{\nu}_\mu N \to \mu^+ X$) scattering covering a broad range of neutrino energies. As can be seen in Fig. 52.1, which shows this data over decades of time and energy, the inclusive cross section approaches a linear dependence on neutrino energy. This behavior is expected for point-like scattering of neutrinos from quarks, an assumption which breaks down at lower energies. Modern measurements of such inclusive neutrino scattering cross sections and their target nuclei are summarized in Table 52.2. The reader is also referred to a recent review of the status of measurements and calculations in the shallow and deep inelastic scattering regions [9].

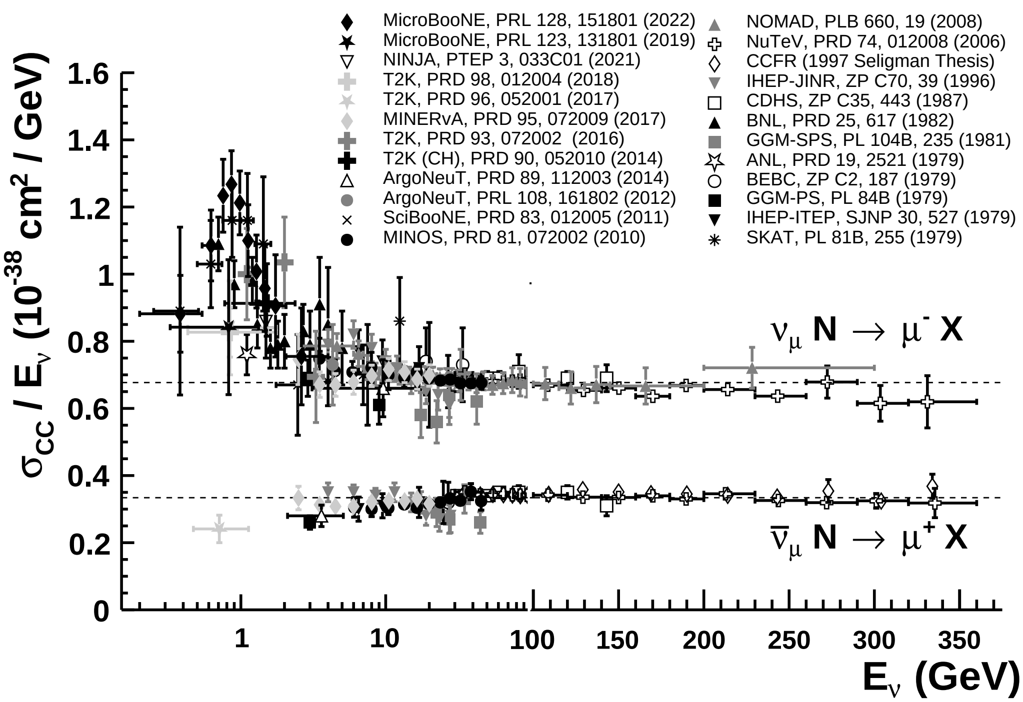

Figure 52.1: Measurements of per nucleon ν_μ and $\overline{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller compared to their CC counterparts.

To provide a more complete picture, differential cross sections for such inclusive scattering processes have also been reported. These include historical measurements on iron from NuTeV [10] and modern measurements on a variety of nuclear targets from ArgoNeuT [11,12], MicroBooNE [13,14], MINERvA [15–18], NINJA [19,20], NOvA [21], and T2K [22,23]. More recently, MINERvA has provided measurements in terms of longitudinal and transverse muon momenta [16,17], MicroBooNE has measured the first triple differential cross sections in argon [24], and T2K has provided the first measurement of the antineutrino inclusive cross section at low energy [25] (Fig. 52.1).

At high energy, the inclusive cross section is dominated by deep inelastic scattering (DIS). Several neutrino experiments have measured DIS cross sections for specific targets and final states, for example, MINERvA has measured ratios of neutrino DIS cross sections on a variety of nuclear targets including lead, iron, and carbon [26, 27]. Other experiments have measured opposite-sign dimuon production, the most recent being from CHORUS [28], NOMAD [29], and NuTeV [30]. Multiple efforts are also now underway to measure inclusive neutrino scattering cross sections at significantly higher neutrino energies, including at the LHC in FASERν [31] and using atmospheric neutrinos in IceCube [32].

Table 52.2: Published measurements of muon neutrino and antineutrino CC inclusive cross sections from modern accelerator-based neutrino experiments.

experiment	measurement	target
ArgoNeuT	ν_μ [11, 12], $\overline{\nu}_\mu$ [12]	Ar
MicroBooNE	ν_μ [13, 24, 33]	Ar
MINERνA	ν_μ [15–18, 26, 27, 34], $\overline{\nu}_\mu$ [34], $\overline{\nu}_\mu/\nu_\mu$ [35]	C, CH, Fe, Pb
MINOS	ν_μ [36], $\overline{\nu}_\mu$ [36]	Fe
NINJA	ν_μ [19, 20], $\overline{\nu}_\mu$ [19]	H_2O, Fe
NOMAD	ν_μ [37]	C
NOvA	ν_μ [21]	CH_2
SciBooNE	ν_μ [38]	CH
T2K	ν_μ [22, 23, 39–41], $\overline{\nu}_\mu/\nu_\mu$ [25]	CH, H_2O, Fe

At lower neutrino energies, the inclusive cross section is an additionally complex combination of quasi-elastic scattering and pion production processes, two areas we discuss next.

52.2 Quasi-elastic scattering

Quasi-elastic (QE) scattering is the dominant neutrino interaction for neutrino energies less than ~ 1 GeV and represents a large fraction of the signal samples in many neutrino oscillation experiments, which is why this process has received considerable attention in recent years. Historically, neutrino (antineutrino) quasi-elastic scattering refers to the process, $\nu_\mu\, n \to \mu^- \, p$ ($\overline{\nu}_\mu\, p \to \mu^+ \, n$), where a charged lepton and single nucleon are ejected in the elastic interaction of a neutrino (or antineutrino) with a nucleon in the target material. This is the final state one would strictly observe, for example, in scattering off of a *free* nucleon target. There were many early measurements of neutrino QE scattering that span back to the 1970's [5]. In many of these initial measurements, bubble chamber experiments employed light targets (hydrogen or deuterium) and required both the detection of the final state muon and single nucleon[2]; thus the final state was clear and elastic kinematic conditions could be verified. The situation is more complicated, of course, for heavier nuclear targets used in modern neutrino experiments. In this case, nuclear effects can impact the size and shape of the cross section as well as the final state composition, kinematics, and topology. Due to intranuclear hadron rescattering and the effects of correlations between target nucleons, additional particles may be ejected in the final state; hence, a QE interaction on a nuclear target does not necessarily imply the ejection of a lepton and a *single* nucleon. One therefore needs to take care in defining what one means by neutrino QE scattering when scattering off targets heavier than hydrogen or deuterium. Because of this, modern experiments tend to instead report cross sections for processes involving pionless (e.g., nucleon-only) final states, often referred to as CC 0π or QE-like reactions in recent literature. Such measurements are summarized in Table 52.3. Many modern experiments have also recently opted to report QE-like cross sections as a function of observed final state particle kinematics. Such measurements can be more difficult to directly

[2] In the case of deuterium, many experiments additionally observed the spectator proton.

compare between experiments but have the advantage of being much less model-dependent and provide more stringent tests of the theory than historical cross sections as a function of derived quantities such as neutrino energy (E_ν) or 4-momentum transfer (Q^2). More recently, new thought has been given to the means for directly comparing experimental measurements produced in these less model-dependent forms [42].

Table 52.3: Published modern measurements of muon neutrino QE and NC elastic scattering cross sections with pionless final states.

experiment	measurement	target
ArgoNeuT	2p [43]	Ar
K2K	M_A [44]	H_2O
MicroBooNE	$\frac{d\sigma}{dp_\mu}$ $\frac{d\sigma}{dp_p}$ $\frac{d\sigma}{d\cos\theta_\mu}$ $\frac{d\sigma}{d\cos\theta_p}$ [45, 46], $\frac{d^2\sigma}{d\delta\alpha_T d\delta p_T}$ [47, 48], $\frac{d^2\sigma}{d\delta p_{Tx} d\delta p_{Ty}}$ [47], 2p [49], Λ [50]	Ar
MINERνA	$\frac{d^2\sigma}{dp_T dp_{\|\|}}$ [51–55], $\frac{d\sigma}{d\delta p_{Tx}}$ $\frac{d\sigma}{d\delta p_{Ty}}$ [56], $\frac{d\sigma}{dp_n}$ $\frac{d\sigma}{d\delta\alpha_T}$ [57], $\frac{d\sigma}{dQ^2}$ [58, 59], 1p [60], $\frac{d^2\sigma}{dE_{avail} dq_3}$ [61], $\frac{d\sigma}{dQ^2}$ [62], $F_A(Q^2)$ [63]	CH,Fe,Pb
MiniBooNE	$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$ [64, 65], M_A [66], NC [67, 68]	CH_2
MINOS	M_A [69]	Fe
NINJA	2p [70]	Fe
NOMAD	M_A, $\sigma(E_\nu)$ [71]	C
Super-K	NC [72]	H_2O
T2K	$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$ [73–78], $\sigma(E_\nu)$ [79], M_A [80], NC [81], $\frac{d\sigma}{d\delta p_T}$ $\frac{d\sigma}{d\delta\alpha_T}$ [82], O/C [76]	CH,H_2O

The topic of neutrino QE scattering began drawing considerable attention following the first double differential cross section measurements of this process that revealed a significantly larger cross section than originally anticipated, predominantly in the backwards muon scattering region [64, 65]. Such an enhancement was observed many years prior in transverse electron-nucleus scattering [83] and was attributed to the presence of correlations between nucleons in the target nucleus. As a result, the impact of such nuclear effects on neutrino QE scattering has recently become the subject of intense experimental and theoretical scrutiny with implications on event rates, nucleon emission, neutrino energy reconstruction, and neutrino versus antineutrino cross sections. The reader is referred to reviews of the situation in [6, 84, 85]. To help drive further progress in understanding the underlying nuclear contributions, pionless (e.g., nucleon-only) cross sections have been reported for the first time in the form of double-differential distributions by MiniBooNE [64, 65], MINERvA [51–55, 61], and T2K [73–78]. Such double-differential cross sections in terms of final state particle kinematics reduce the model-dependence of the reported data, provide the most robust measurements available, and allow a more rigorous two-dimensional test of the underlying nuclear theory. MicroBooNE, MINERvA, and T2K have been especially prolific in recent years in probing this interaction process (Table 52.3). Neutrino experiments have also launched dedicated studies of the hadronic side of these interactions, including ArgoNeuT [43,86], MicroBooNE [45,46], MINERvA [60, 87], and T2K [82]. MINERvA has been the first modern experiment to measure neutron emission in antineutrino interactions [88] and has simultaneously measured neutrino QE cross sections on a variety of nuclear targets ranging from carbon to lead [55]. ArgoNeuT [43], MicroBooNE [49], and NINJA [70] have explored two-proton final states. T2K has probed ratios of oxygen to carbon [76, 89], asymmetries between neutrino and antineutrino scattering [77], and simultaneous measurements both on and off axis to the neutrino beam [78]. In addition, the exploration of transverse kinematic variables and momentum imbalances in pionless neutrino scattering is allowing better constraints on the various nuclear contributions to the cross section. Such scrutiny includes important evaluations from MicroBooNE [47, 48], MINERvA [51, 52, 56, 57] and T2K [82]. With the MiniBooNE results having first revealed these additional complexities in neutrino-nucleus QE scattering, measurements from multiple neutrino experiments, on multiple targets, and using a variety of kinematic information have been crucial in gaining a better handle on the underlying nuclear physics impacting neutrino-nucleus interactions. What we once thought was “simple” QE scattering is in fact not so simple.

Equally important, neutrino experiments such as MINERvA have revisited the extraction of the axial form factor from light target data using modern higher statistics data sets [63]. In addition to such charged current investigations, measurements of the neutral current counterpart of this channel have also been performed. The most recent NC elastic scattering cross section measurements include those from BNL E734 [90], MiniBooNE [67, 68], Super-K [72], and T2K [81]. A number of measurements of the Cabibbo-suppressed antineutrino QE hyperon production cross section have additionally been reported [91, 92], most recently by MicroBooNE [50]. As an exciting new addition, there have also been the first observations of the very challenging-to-detect coherent elastic neutrino-nucleus scattering (CEνNS) process now in multiple nuclei by COHERENT [93, 93, 94].

52.3 Pion Production

In addition to such elastic scattering processes, neutrinos can also inelastically scatter producing a nucleon excited state (Δ, N^*). Such baryonic resonances quickly decay, most often to a nucleon and single-pion final state. Historically, experiments have measured various exclusive final states associated with these reactions, the majority of which have been on hydrogen and deuterium targets [5]. There have been several recent re-analyses of this data to better understand the consistency between data sets [95], nucleon form factors [96], and non-resonant contributions [97]. Also, modern measurements of neutrino-induced pion production have since been performed on a variety of nuclear targets (Table 52.4).

In addition to resonance production processes, neutrinos can also coherently scatter off of the entire nucleus and produce a distinctly forward-scattered single pion final state. Both CC ($\nu_\mu A \to \mu^- A \pi^+$, $\overline{\nu}_\mu A \to \mu^+ A \pi^-$) and NC ($\nu_\mu A \to \nu_\mu A\pi^0, \overline{\nu}_\mu A \to \overline{\nu}_\mu A\pi^0$) processes are possible in this case. Even though the level of coherent pion production is small compared to their resonant counterpart, observations exist across a broad energy range and on multiple nuclear targets [135]. More recently, several modern neutrino experiments have either measured or set limits on coherent pion production cross sections including ArgoNeuT [98], K2K [102], MINERvA [109, 111, 113], MiniBooNE [123], MINOS [124], NOMAD [125], NOvA [126], SciBooNE [128, 130], and T2K [102].

As with inclusive and quasi-elastic scattering, a new appreciation for the significance of nuclear effects has also surfaced in pion production physics, again due to the use of heavy nuclear targets in modern neutrino experiments. Many experiments have been careful to report cross sections for

Table 52.4: Summary of modern measurements of NC and CC scattering cross sections involving a single pion or multiple pions in the final state.

experiment	$\pi^{\pm}$	π^0	target
ArgoNeuT	CC [98, 99]	NC [100]	Ar
K2K	CC [101, 102]	CC [103], NC [104]	CH, H_2O
MicroBooNE	–	CC [105], NC [106]	Ar
MINERνA	CC [107–114]	CC [108, 115–117], NC [118]	C, CH, H_2O, Fe, Pb
MiniBooNE	CC [119, 120]	CC [121], NC [122, 123]	CH_2
MINOS	–	NC [124]	Fe
NOMAD	–	NC [125]	C
NOvA	–	NC [126, 127]	C
SciBooNE	CC [128]	NC [129, 130]	CH
T2K	CC [131–134]	–	CH, H_2O

various detected final states, thereby not correcting for large and uncertain nuclear effects (e.g., pion rescattering, charge exchange, and absorption) which can introduce significant sources of uncertainty and model dependence. Providing the most comprehensive survey of neutrino single-pion production to date, MiniBooNE has published a total of 16 single- and double-differential cross sections for both the final state muon (in the case of CC scattering) and pions in these interactions; thus, providing the first measurements of such final state kinematic distributions [119–122]. At similar neutrino energies, T2K has provided new data [131] including the first measurement of the Adler angles in neutrino-nucleus scattering [133] and the first exploration of transverse kinematic imbalances in pion production processes [134]. MINERvA has produced a similar accompaniment of measurements at higher neutrino energies [108, 110, 112, 116] and uniquely on multiple nuclear targets [114]. Importantly, MINERvA has been working towards an improved nuclear model [117] that can potentially describe all of the pion reaction channels simultaneously, an issue that many experiments have struggled with up until now [108]. ArgoNeuT [99, 100] and MicroBooNE [105, 106] have since been adding new information on single pion production in argon. Regardless of the interaction channel or target material, differential cross section measurements in terms of observed final state particle kinematics are preferred for their reduced model dependence and for the additional kinematic information they provide. Such a new direction has been the focus of modern measurements as opposed to the reporting of more model-dependent, historical cross sections as a function of E_ν or Q^2. Together with similar results for other interaction channels, a better understanding and modeling of nuclear effects will be possible moving forward. MINERvA [136] has already taken a large step in this direction by explicitly tuning the physics in existing neutrino event generators to best fit the experimental data on pion production.

It should be noted that baryonic resonances can also decay to multi-pion, other mesonic (K, η, ρ, etc.), and even photon final states. Experimental results for these channels are typically sparse or non-existent. More recently, MicroBooNE has produced the first measurement of neutrino-induced η production on argon [137]. Photon production processes can comprise an important background for $\nu_\mu \to \nu_e$ appearance searches in some detectors and thus have become the focus of recent experimental investigations, most notably in NOMAD [138] and T2K [139, 140]. There have also been several recent measurements of kaon final states produced in neutrino NC and CC scattering in MINERvA [141–143] that are providing needed background constraints for certain nucleon decay searches.

52.4 Electron Neutrino Scattering

The aforementioned cross section measurements are all for either muon neutrino or muon antineutrino scattering. With the production of predominantly muon neutrino beams for neutrino oscillation studies, the availability of electron neutrino scattering data is by construction limited. However, for the first time, measurements of electron neutrino scattering cross sections are being produced by a variety of modern neutrino experiments (Table 52.5). Such measurements are important as they verify our assumptions about lepton universality and validate the use of muon neutrino data to constrain electron neutrino interaction predictions. For lower energy and historical electron neutrino cross section measurements, the reader is directed to reference [5].

Table 52.5: Published measurements of electron neutrino and antineutrino cross sections from modern accelerator-based neutrino experiments.

experiment	CC inclusive	QE-like	π production	target
ArgoNeuT	[144]	-	-	Ar
COHERENT	[145]	-	-	I
MicroBooNE	[146, 147]	[148]	-	Ar
MINERνA	-	[149]	-	CH
NOvA	[150]	-	-	CH_2
T2K	[151–153]	-	-	CH, H_2O

52.5 Outlook

Neutrino experiments continue to produce critical neutrino scattering measurements on nuclei as they accumulate increased statistics and pursue new ways of reporting their measurements. Analysis of a broad energy range of data from MINERvA is providing some of the most detailed analysis of nuclear effects in neutrino interactions by examining multiple nuclei in a single experiment. Data from ArgoNeuT, MicroBooNE, ICARUS and soon also SBND are probing deeper into complex neutrino final states using the superior capabilities of liquid argon time projection chambers, while the T2K and NOvA near detectors continue to collect high statistics samples in intense neutrino beams. Together with dedicated discussions between experiments on how best to report neutrino cross section measurements [154] and with accompanying work being advanced by theorists to further improve nuclear model calculations [6], we are starting to significantly advance our understanding of neutrino-nucleus scattering.

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