Snowmass2021 - Letter of Interest

Neutrino cross-sections and interaction physics

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other): NF04, NF05, NF06, NF10, TF11

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Abstract:

Interactions of atmospheric and astrophysical neutrinos in detectors have a center-of-mass energy reach far beyond man-made accelerators. Studies of neutrino absorption in the Earth (sensitive to the cross-section) and of neutrino interactions in ice can provide information on both Standard Model (SM) processes and beyond-the-Standard-Model (BSM) physics. Measurements of ν-N cross-sections at energies up to 10^{20} eV can probe parton distributions down to Bjorken $x \approx 10^{-7}$ at large Q^2. Both types of studies probe a variety of BSM topics, including leptoquarks, extra dimensions, supersymmetry and sphalerons.

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Neutrinos from man-made accelerators, with energies of up to ~ 300 GeV, have allowed us to measure neutrino-nucleon ($\nu - N$) cross sections up to center-of-mass energies of $\sqrt{s} \approx 25$ GeV. Cosmic accelerators offer us the opportunity to study neutrinos with energies far higher, to probe predictions of Standard Model (SM) and test beyond-the-Standard-Model (BSM) theories. IceCube has observed neutrinos with energies above 5 PeV, and despite limited statistics, already has used them to measure cross sections up to $\sqrt{s} \approx$ 1 TeV. In this LoI, we show how future experiments will probe SM and BSM physics at higher energies.

Measuring the high-energy neutrino-nucleon cross section The idea of using absorption of high-energy neutrinos in the Earth to measure the ν-N cross section dates back to the mid 1970s[1]. The $\nu - N$ cross section grows with neutrino energy, reducing the length of the path that it travels underground. The cross section is extracted from the zenith angle-dependence of neutrino absorption. In the six years since the last Snowmass survey[2], these measurements have become reality.

IceCube has measured the ν-N cross section at energies from 10 TeV to 1 PeV, as shown in Fig. 1. That analysis used ν_μ, while another extended the energy reach to 10 PeV - using starting events that are rich in ν_e while dividing the events into decade-wide bins in neutrino energy. Both found consistency with the SM, but the latter had much larger uncertainties[3]. A third independent analysis found a similar result[4]. IceCube also measured the neutrino inelasticity distribution, and used that to constrain both the $\nu/\overline{\nu}$ ratio and charm production rate in neutrino interactions[5].

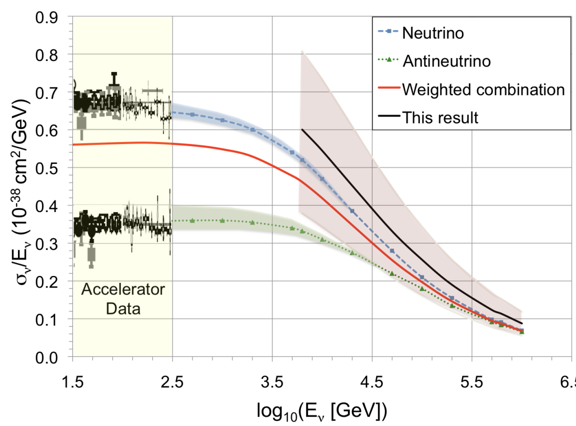

Figure 1: The ν_μ-nucleon cross-section measured by IceCube, compared with accelerator measurements.

ANITA has observed radio pulses from two steeply-upward-going events with estimated energies around 0.1 EeV, with polarity opposite that expected for reflections from cosmic-ray air showers[6]. If these are from neutrinos, their apparent path length through the Earth requires a cross-section considerably smaller than predicted by the SM.

The experimental landscape Looking ahead, new experiments will collect much more data, using a variety of detection techniques to cover a wider energy range. Optical Cherenkov detectors—IceCube, IceCube-Gen2[7], ANTARES, KM3NeT, Baikal-GVD[8], P-ONE[9]—will provide data for much more precise measurements of the TeV–PeV cross section. With 10 years of IceCube data, improved event selection and analysis, and reduced systematic errors (enabled by the IceCube Upgrade), it should be possible to reach 10% uncertainty in decade-wide energy bins compared to the 40% uncertainty in a single bin in the ν_μ analysis mentioned above. Separate cross-section measurements using through-going tracks (mainly ν_μ) and starting events (mainly ν_e) could probe the cross sections for different flavors.

At higher energies, up to the EeV scale, neutrino discoveries could allow for cross section measurements up to $\sqrt{s} \approx 100$ TeV, where the uncertainties in the SM cross-section predictions are larger[4]. Here, the Earth is nearly opaque to neutrinos, so most events will be observed near the horizon; zenith angle resolution is important for absorption studies. Upcoming experiments, including AugerPrime[10], the Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)[11], the Giant Radio Array for Neutrino Detection (GRAND)[12], RNO[13;14] and ARIANNA-200[15] will monitor much larger volumes in the hope of discovering the long-sought cosmogenic, or 'GZK' neutrinos, produced when ultra-high-energy cosmic rays interact with cosmic photon backgrounds. A separate LoI describes the experiments that target EeV neutrinos[16].

Measuring inelasticity at high energies Inelasticity measurements probe the fraction of the neutrino energy transferred to the struck nuclear target. This is currently only possible for starting-track ν_μ interactions, since it requires separate measurements of the shower (cascade) and outgoing lepton. IceCube has measured the inelasticity distribution from 1 TeV to 1 PeV using 5 years of data[5] and found that the mean inelasticity decreases as the neutrino energy rises, in accord with the SM. The inelasticity distribution is also sensitive to charm production in neutrino interactions. The IceCube analysis observed non-zero charm production - at more than 90% CL.

At energies below about 20 TeV, ν and $\overline{\nu}$ have significantly different inelasticity distributions. IceCube used this to measure the $\nu : \overline{\nu}$ ratio in atmospheric neutrinos. If atmospheric neutrinos were suppressed with a surface or self-veto for downward going events, it could be possible to measure this ratio in astrophysical neutrinos. For low-energy (below 1 TeV) studies, nuclear corrections need to be considered, since the inelasticity depends on quark distributions at large Bjorken$-x$, and through that on the neutron:proton ratio[17].

New types of neutrino interactions are likely to have inelasticity distributions that differ significantly from deep inelastic scattering. Electromagnetic interactions (where the photon interacts with the Coulomb field of the nucleus) produce shower-free events with an apparent inelasticity of zero[18]. In the SM, these are relatively rare - at most a few percent of the interactions - so observing them should be a challenge. Leptoquark interactions can also be visible in inelasticity distributions[19].

Looking ahead, IceCube Gen2 and KM3NeT will both benefit from their much larger contained volumes, and, at energies above 100 TeV, data samples 100 times larger than those used for the current analyses are obtainable. This should allow for quite precise measurements.

Testing SM and BSM predictions Measuring the neutrino cross section is important for both SM and BSM tests. Within the SM, the neutrino cross-section probes quark distributions at very low Bjorken$-x$ values and large Q^2. A 10^{20} eV neutrino typically probes a Bjorken$-x$ of 10^{-7}, significantly beyond the reach of the HERA ep collider. Nuclear effects, like shadowing, are small, but not completely negligible[17].

Many BSM physics models predict a large increase in cross-section above a threshold energy (often a soft threshold)[20]. Already, limits from high-energy neutrinos are comparable to those from hadron colliders. For example, leptoquarks lead to a large increase in the neutrino-quark cross-section when the center of mass energy reaches the leptoquark mass[21]. If there are extra rolled-up dimensions with size d, then when the momentum transfer reaches $\hbar/d$, the cross-section will similarly increase[22]. A sufficiently energetic cosmic neutrino interaction may also trigger transitions in the topologically non-trivial weak SU(2) vacuum, corresponding to the creation of sphalerons with TeV mass[23].

Radio-detection experiments should also be sensitive to inelasticity, and these measurements can provide key information about possible BSM processes. At energies above 10^{16} eV, the Landau-Pomeranchuk-Migdal effect lengthens electromagnetic (EM) showers - but not hadronic showers[24]. It may be possible to separate the radiation from the EM and hadronic components, and thereby determine the inelasticity,[25] because they will have different radio spectra[26] and Cherenkov cone widths. At still higher energies, EM showers divide into multiple separate subshowers. By identifying and measuring the energy of the hadronic shower and one or more subshowers, it should be possible to determine the event inelasticity[5].

In conclusion, studies of neutrino interactions in terrestrial detectors and in the Earth using next-generation detectors offer a clear path to higher precision measurements at energies far beyond the reach of terrestrial accelerators and could offer us the first sign of new physics beyond the Standard Model.

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