Future determination of the neutrino-nucleon cross section at extreme energies.

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Future detectors of cosmic rays, such as EUSO and OWL, can test the Standard Model predictions for the neutrino interactions at energies well beyond the reach of any terrestrial experiment. The relative rates of horizontal and upgoing air showers, combined with the angular distribution of upgoing air showers will allow one to measure the neutrino-nucleon cross section at $\sqrt{s} \sim 10^5 \text{ GeV}$ or higher.

Detection of ultrahigh-energy (UHE) neutrinos will mark the advent of UHE neutrino astronomy, allowing the mapping on the sky of the most energetic and most distant sources in the Universe. In addition, the prospects for detection of the neutrino-induced upgoing air showers (UAS) by the ground-level fluorescence detectors, such as HiRes, Telescope Array, and Pierre Auger, as well as the future orbiting detectors, present an opportunity to conduct a particle physics experiment and measure the neutrino cross section $\sigma_{\nu N}$ at an unprecedented center-of-mass energy $10^5 - 10^6 \text{ GeV}$. The relative rates of the horizontal air showers (HAS) initiated by neutrinos depend on $\sigma_{\nu N}$ in such a way that the cross section can be determined without a precise knowledge of the incident neutrino flux. Moreover, the angular distribution of UAS provides an additional and independent information about the cross section.

The first question is, of course, whether there is a sufficient flux of neutrinos to detect. Observations of ultrahigh-energy cosmic rays (UHECR) imply the existence of a related flux of ultrahigh-energy neutrinos generated in the interactions of UHECR with cosmic microwave background radiation. In addition, active galactic nuclei, gamma-ray bursts, and other astrophysical objects can produce a large flux of neutrinos. Finally, if the solution to the puzzle of UHECR involves Z-bursts, there is a strong additional flux of ultrahigh-energy neutrinos. The flux of UHE neutrinos at energies $10^{18} - 10^{20} \text{ eV}$ is uncertain. However, as discussed below, the proposed measurement of the neutrino cross section is not sensitive to these uncertainties.

Calculations of the neutrino-nucleon cross section $\sigma_{\nu N}$ at $10^{20} \text{ eV}$ necessarily use an extrapolation of parton distribution functions and Standard Model parameters far beyond the reach of present experimental data. The resulting cross section $\sigma_{\nu N}$ at $10^{20} \text{ eV}$ is $\sim 10^{-31} \text{ cm}^2$. It is of great interest to compare this prediction with experiment to test the small-$x$ behavior of QCD, as well as the possible contributions of new physics beyond the electroweak scale.

For the purposes of such a measurement, we assume the cross section to be a free parameter bounded from below by the value $\sim 2 \times 10^{-34} \text{ cm}^2$ measured at HERA at $\sqrt{s} = 314 \text{ GeV}$. (This corresponds to a laboratory energy $E_\nu = 5.2 \times 10^{13} \text{ eV}$ of an incident neutrino.)

UHE neutrinos are expected to arise from pion and muon decays. The subsequent oscillations generate a roughly equal fraction of each neutrino flavor. Tau neutrinos interacting below the surface of the Earth can create an energetic $\tau$-lepton, whose decay in the atmosphere produces an UAS.

It is clear that, for smaller values of the cross section, the Earth is more transparent for neutrinos, so that more of them can interact just below the surface and produce a $\tau$ that can come out into the atmosphere. As long as the mean free path $\lambda_\nu$ is smaller than the radius of the Earth, the rates of UAS increase with $\lambda_\nu \propto 1/\sigma_{\nu N}$. The rates of HAS, however, are proportional

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to $\sigma_{\nu N}$; they decrease for a smaller cross section. The comparison of the two rates, shown in Fig. 1, can allow a measurement of the cross section which is practically independent of the uncertainties in the incident neutrino flux.

In addition, the angular distribution of UAS alone can be used as an independent measurement of the cross section. The peak of the angular distribution of UAS occurs when $\cos \theta_{\text{peak}} \approx \lambda_{\nu} / 2R_{\oplus}$, which depends on the cross section.

It is comforting to know that the program of UHE neutrino astronomy, which is one of the goals of EUSO and OWL, is not at risk, regardless of any theoretical uncertainties in the neutrino cross section. For a larger cross section, HAS are more frequent than UAS, while for a smaller value UAS dominate. Nevertheless, the total rates of combined events remain roughly constant for a wide range of $\sigma_{\nu N}$, as shown in Fig. 1.

On the other hand, some of the reported bounds on the neutrino flux are directly affected by the uncertainties in the neutrino-nucleon cross section. For example, the reported bounds on the UHE neutrino flux due to the non-observation of neutrino-initiated HAS and of radio signals produced by neutrino interactions near the surface of the moon are weaker if the cross section is smaller.

To conclude, the future neutrino cosmic-ray experiments can determine the neutrino-nucleon cross section at energies as high as $10^{11}$ GeV, or higher, by comparing the rates of UAS with those of HAS; or by measuring the angular distribution of UAS events. Hence, there is an exciting opportunity do a particle physics experiment using a natural “beam” of cosmic UHE neutrinos in the near future. In addition, the overall prospects for UHE neutrino astronomy are not marred by possible theoretical uncertainties in the value of the neutrino-nucleon cross section: the total number of horizontal and upgoing events remains sufficient for a wide range of $\sigma_{\nu N}$.

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