INTERACTIONS OF ULTRAHIGH-ENERGY NEUTRINOS

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Future detection of ultrahigh-energy neutrinos will open a new window on physics at center-of-mass energy $10^5$ GeV and higher. In particular, observations of neutrino-initiated showers will help test the Standard Model predictions for the neutrino-nucleon cross section.

The anticipated detection of ultrahigh-energy (UHE) neutrinos will mark the beginning of UHE neutrino astronomy and will provide new opportunities for particle physics. The prospects for detection of upgoing neutrinos by ICE CUBE, as well as the ground-level fluorescence detectors, such as HiRes and Pierre Auger, and orbiting detectors, such as EUSO, present an opportunity to conduct a particle physics experiment and to measure the neutrino-nucleon cross section $\sigma_{\nu N}$ at an unprecedented center-of-mass energy $10^5 - 10^6$ GeV. The relative rates of the horizontal air showers (HAS) and UAS 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.

There are several reliable predictions regarding the flux of UHE neutrinos. 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, some of the proposed explanations of the puzzle of UHECR predict a strong additional flux of ultrahigh-energy neutrinos. The flux of UHE neutrinos at energies $10^{18} - 10^{20}$ eV is uncertain. However, as discussed below, the proposed measurement of the neutrino cross section is not very sensitive to
these uncertainties.\(^6\)

Calculations of the neutrino-nucleon cross section \(\sigma_{\nu N}\) at \(10^{20}\) 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 \(^{14}\) at \(10^{20}\) eV is \(\sim 10^{-31}\) 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.\(^{18}\)

For the purposes of such a measurement, we assume the cross section to be a free parameter bounded from below by the value \(\sim 2 \times 10^{-34}\) cm\(^2\) measured at HERA at \(\sqrt{s} = 314\) GeV. (This corresponds to a laboratory energy \(E_\nu = 5.2 \times 10^{13}\) 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 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\(^6\) 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 HAS, 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\(^{15}\) and of radio signals produced
Figure 1. The air shower probability per incident tau neutrino as a function of the neutrino cross section. The incident neutrino energy is $10^{20}$ eV and the assumed energy threshold for detection of UAS is $E_{th} = 10^{18}$eV for curve 1 and $10^{19}$eV for curve 2.

by neutrino interactions near the surface of the moon are weaker if the cross section is smaller.

To summarize, the future neutrino 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. Therefore, there is an exciting opportunity do a particle physics experiment using neutrinos produced by natural astrophysical sources.

Acknowledgments

This work was supported in part by the DOE grant DE-FG03-91ER40662.

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