New physics with ultra-high-energy neutrinos

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Now that PeV neutrinos have been discovered by IceCube, we optimistically entertain the possibility that neutrinos with energy above 100 PeV exist. We evaluate the dependence of event rates of such neutrinos on the neutrino-nucleon cross section at observatories that detect particles, atmospheric fluorescence, or Cherenkov radiation, initiated by neutrino interactions. We consider how (i) a simple scaling of the total standard model neutrino-nucleon cross section, (ii) a new elastic neutral current interaction, and (iii) a new completely inelastic interaction, individually impact event rates.

IceCube’s announcement of a population of neutrino induced events with shower energies above 1 PeV [1] has created excitement in the neutrino astrophysics community. The long awaited discovery of high energy cosmic neutrinos has arrived. Prompted by this discovery, we revisit the problem of extracting neutrino-nucleon cross section information from currently running and proposed cosmic neutrino experiments. A variety of candidates for sources of the observed neutrinos have been put forward, and many ideas for testing models of new physics and old have been advanced, but the study of methods to tease out new physics signals from data has not previously gained attention. We address this methodology for new physics here, by summarizing the dependence of different detector’s acceptance of cosmic neutrinos on the cross sections relevant to their propagation and detection. We restrict ourselves to ultra-high-energy (UHE) neutrinos, i.e., those with energies above 100 PeV. Included in “cross sections” are any new contributions to neutrino physics. “Acceptance” includes all of the calculational factors in the event rate except the flux of incident neutrinos.

Neutrino detectors naturally segregate into one of three types depending on what aspect of the neutrino-initiated shower is detected: particles, fluorescence radiation, and radio/visible Cherenkov radiation. Particle detectors include Pierre Auger Observatory (PAO) [2] and Telescope Array (TA) [3], fluorescence detectors include PAO [2], TA [3] and Extreme Universe Space Observatory (EUSO) [4], radio frequency Cherenkov detectors include ANITA [5], ARA [6] and ARIANNA [7], building on the early searches by the GLUE [8] and RICE [9] experiments, while the visible Cherenkov detector is IceCube and its expansion to Gen2 [10], which uses deep-ice optical detection. The atmosphere provides the detection medium for PAO, TA and EUSO, while the Antarctic ice provides the detection medium for ANITA, ARA, ARIANNA, and IceCube-Gen2.

New physics possibilities naturally segregate into modified total (TOT) cross section, modified neutral current (NC) cross section (including quasi-elastic when the final state charged lepton does not contribute to the shower, as is the case with produced muons at all energies and produced taus above $\sim 100$ EeV), and enhanced absorption (BH) cross section. A modified total cross section may result from QCD saturation effects or from new strong interactions like technicolor. An example of a new elastic neutral current-like interaction is provided by enhanced graviton exchange. An example of an absorptive enhancement is possible micro black-hole production, which is predicted in low scale gravity models. With this in mind, we label the absorptive enhancement by “BH”. By appropriate comparisons between rates of upward and downward going neutrinos in the different experiments (tabulated in Table 1), we can isolate the TOT, NC and BH cross section dependences. Then, deviations of TOT, NC, or BH cross sections from standard model (SM) expectations would indicate new physics and categorize its potential origin.

Following Ref. [11], we parametrize charged current (CC) and NC interactions with the same inelasticity (fractional energy transfer to the baryonic target, or y value) as in the SM via $\alpha_{CC} \equiv \sigma_{CC}/\sigma_{TOT}$ and $\alpha_{NC} \equiv \sigma_{NC}/\sigma_{TOT}^NC$, and parametrize a new completely inelastic cross section (also normalized to $\sigma_{TOT}^NC$) by $\alpha_{BH}$. Then, for the SM, $(\alpha_{CC}, \alpha_{NC}, \alpha_{BH}) = (r_{CC}, r_{NC}, 0) \approx (0.71, 0.29, 0)$ [12], with $r_{CC} = \sigma_{CC}/\sigma_{TOT}$ and $r_{NC} = \sigma_{NC}/\sigma_{TOT}^NC$. A scenario in which the total cross section is scaled by $\alpha$, i.e., $\sigma_{TOT} = \alpha \sigma_{TOT}^SM$, is described by $(\alpha_{NC}, \alpha_{NC}, \alpha_{BH}) = (r_{CC}, r_{NC}, 0)$. Similarly, the enhanced NC case with $\Delta \sigma_{NC} = \alpha \sigma_{NC}^{SM}$ is described by $(r_{CC}, r_{NC}, 1 + \alpha), 0$, and the BH case with $\sigma_{BH} = \alpha \sigma_{TOT}^SM$ is described by $(r_{CC}, r_{NC}, \alpha)$ [1]. In what follows, we distin-

$^1$ Note that in Ref. [11], the NC case is described by
guish between the attenuation cross section, $\sigma_{\text{att}}$, which is relevant for up-going/skimming neutrinos, and the showering cross section, $\sigma_{\text{sh}}$. Note that $\sigma_{\text{sh}}^{\text{SM}}$ is $\sigma_{\text{TOT}}^{\text{SM}}$ weighted by the energy in the visible shower, i.e., the total interaction energy minus the non-showering energies of final state neutrinos and track-producing charged leptons; see Table I.

The cross section weighted by inelasticity, called the attenuation cross section, for flavor $f$ in the standard model can be written as

$$\sigma_{\text{att}}^{\text{SM} f} = \sigma_{\text{CC}}^{\text{SM}} + \sigma_{\text{NC}}^{\text{SM}} \times \frac{y_f}{y_{\text{NC}}} \approx \sigma_{\text{CC}}^{\text{SM}} + 0.2\sigma_{\text{NC}}^{\text{SM}} \approx 0.77\sigma_{\text{TOT}}^{\text{SM}}. \quad (1)$$

The attenuation cross sections are the same for the three neutrino flavors (labeled $f = e, \mu, \tau$) because $\frac{y_f}{y_{\text{NC}}} \approx 0.2$ is the mean inelasticity factor for the NC cross section at energies above 100 PeV [12]. The final form in Eq. 1 results from the relation $\sigma_{\text{CC}}^{\text{SM}} \approx 2.5\sigma_{\text{NC}}^{\text{SM}}$, independent of energy at UHE for a wide range of cross section estimates [12]. Note that the attenuation cross section allows for neutrinos that scatter by the NC and continue with 80% of the original neutrino energy to create a signal in the detector.

For showering in dense media and detection by radio Cherenkov signals at energies above $10^4$ PeV, a first approximation is $\sigma_{\text{sh}}^{\text{SM}} \approx 0.21\sigma_{\text{TOT}}^{\text{SM}}$ for $\nu_e$, $\nu_\mu$, and $\nu_\tau$, with additional contributions from the electromagnetic shower in the $\nu_e$ case, and from $\tau$ decay in matter in the $\nu_\tau$ case, with each new contribution falling with energy. For the effective showering cross sections, factors like the Landau-Pomeranchuk-Migdal (LPM) effect [13] and the $\tau$ lifetime (48 $\left(\frac{E}{\text{GeV}}\right)$ km) introduce significant energy dependence into the inelasticity factors [2, 1, 3, 4, 6].

First consider the case of downward neutrino-initiated shower events. In the SM, neutrino showers are well-separated in the vertical atmosphere from cosmic-ray showers: The first interaction of UHE cosmic rays occurs high in the atmosphere ($\sigma_{\text{ON}} \sim 100$ mb); on the contrary, UHE neutrinos interact low in the atmosphere, if at all, where the atmosphere is exponentially more dense. For down-going neutrinos observed from surface arrays like PAO and TA, or from an airborne observatory like EUSO, the interaction height ranges from ten meters water equivalent for the vertical atmosphere, to thirty times that for horizontal events [14]. The SM neutrino cross section at $10^{20}$ eV is $5 \times 10^{-31}$ cm$^2$, and so the optical depth (a measure of the mean number of interactions, or equivalently the interaction probability in the case of an optically thin medium) for an incident vertical neutrino is $0.5 \times 10^{-4}$, and $6 \times 10^{-4}$ for an incident horizontal neutrino. It is unlikely that any new physics cross section would be enormously larger than the SM cross section, and so we do not anticipate enormously larger optical depths.

A consequence of the same mean inelasticity for all flavors is that the NC contribution to the shower signal is flavor-independent. The CC flavor cases have different contributions to the shower-calorimetry. A $\nu_e$ CC interaction releases 20% of the energy into a hadron shower and the remaining 80% into an electromagnetic shower as the electron/positron quickly ranges out, so it fully attenuates. Its contribution to showering depends on the medium and the detection method. The electromagnetic component contributes fully to the shower detection in air (for PAO, TA and EUSO), but the LPM effect in dense media limits its role in generating signal in Cherenkov detectors (ANITA, ARA, ARIANNA and IceCube-Gen2) to energies below an EeV.

The $\nu_\mu$ and $\nu_\tau$ collisions, whether CC or NC, transfer only their hadronic recoil portion to showers. However, at energies below $10^4$ to $10^5$ PeV, the $\tau$ produced in a CC $\nu_\tau$ interaction decays quickly enough to provide a significant addition to the showers [15]. The detectability of NC events is suppressed because the NC cross section is $2/5$ of the CC cross section, and NC events only contain the hadronic shower energy, which at UHE is only 20% of the incident energy. As a first approximation, the highest energy horizontal showers will be all CC $\nu_e$, or totally inelastic, new-physics generated.

For up-going events observable at the Earth’s surface, the absorption of the initial neutrino by Earth-matter greatly restricts the solid angle of the emerging event. Except for very horizontal events, the Earth is opaque to UHE neutrinos. In addition, we have seen that the optical depth for a neutrino to interact in our atmosphere is quite small. Thus, the up going neutrino must interact

$$\nu_{\ell_{\text{CC}}}, y_{\text{NC}} + 0, 0) \text{ because there } \Delta \sigma_{\text{NC}} = \alpha \sigma_{\text{TOT}}^{\text{SM}}.$$
in the Earth, close enough to the Earth’s surface to allow a charged lepton to emerge and shower. Energy losses for the charged lepton in the Earth, and the requirement of a shower, preclude all charged leptons but the tau from showering in the atmosphere does not affect Cherenkov experiments. Therefore, when the Earth-absorption effects become important when the energy grows. The \( \tau \) decay length cannot be ignored relative to the Earth’s radius, i.e., when order \( \lambda_{\text{att}} \sim 1/\sin \theta_h \) is the angle between the entry direction and the horizon. Consequently, there is a reduction factor of }\lambda_{\text{att}} \sim 1/\sigma_{\text{att}} \text{ in the expected acceptance. When the } \tau \text{ lepton must pass below or above the projection area of surface detectors before showering, as in the EUSO and PAO/TA experiments, this projection carries another sin } \theta_h \text{ penalty factor, which shows up as the square in the denominators of the PAO/TA/EUSO “up” rows in Table I.}

On the other hand, the reduced solid angle of the shower in the atmosphere does not affect Cherenkov experiments like ANITA, IceCube-Gen2, ARA and ARIANNA, even though the latter two experiments consist of planar, surface detectors. This is because for these ex-
Experiments the showers develop in sub-surface ice, thereby enlarging the detector volume. Thus, for Cherenkov detectors, there is only the single reduction factor in the acceptance, $\lambda_{\text{att}} \sim 1/\sigma_{\text{att}}$. Moreover, Cherenkov detection is not limited to $\nu_e$ interactions, but rather to all events that produce showers, regardless of flavor.

Details of the role that SM cross sections play in determining the acceptance for a given experimental geometry and detection method have been elaborated in the literature. We have drawn on these sources for the comments made above, and summarize these comments in the “SM” column of Table I.

Next we turn to the effects of possible new physics. The case of purely new NC physics, $\Delta\sigma_{\text{NC}}$, adds $< y_{\text{NC}}> \Delta\sigma_{\text{NC}}$ to the showering cross section. To estimate the significance of new physics effects in the NC sector, we can write the attenuation factor for neutrinos propagating through the Earth as

$$\sigma_{\text{att}}^{\text{SM}} + < y_{\text{NC}}> \Delta\sigma_{\text{NC}} = \sigma_{\text{att}}^{\text{SM}} + (1 + \alpha) \Delta\sigma_{\text{NC}}$$.

Because of the small inelasticity, it is seen that an enhancement of $1 + \alpha \approx < y_{\text{NC}}> \sim 5$ is needed to make $\sigma_{\text{att}}^{\text{NC}}$ comparable to $\sigma_{\text{att}}^{\text{SM}}$. This factor of 5 is relevant for the EUSO experiment, for example. Downward air showers recorded by EUSO are estimated to receive roughly equal contributions from $\nu_{\tau}$ CC-initiated showers and $\tau$ decay showers up to 10 EeV, but above 100 EeV the $\tau$ showers are a few percent or less because the increased decay length carries the $\tau$ outside the observable atmospheric volume before it decays. In Table I the cross section dependence for EUSO (down) under $\Delta\sigma_{\text{NC}}$ is then $\sigma_{\text{att}}^{\text{SM}}$ for flavors $e$ and $\tau$ for neutrino energies up to $10^{4.5}$ PeV and for just $e$ above that. The contribution of $\Delta\sigma_{\text{NC}}$ will be small unless $\alpha \gtrsim 5$.

Similar considerations lead us to the entries in Table II for new physics that scales the total SM cross section, and for purely inelastic neutrino absorption (BH).

In summary, the approximate independence of the up event rate in volume detectors from the total neutrino cross section, and the fact that the down event rate is proportional to the flux and the cross section, enables the up/down ratio to isolate the features of the cross section. Since only the deposited energy of interaction is observed, further analysis is needed to link the observed spectrum of events directly to the cross section’s dependence on the neutrino energies corresponding to the events. In the case of surface detectors, the up event rate as a function of the grazing angle can reveal anomalous suppression of up versus down events when new physics is present. A known $\nu_{\tau}$ cross section offers an additional handle on the interpretation of the up versus down event rates. We believe the overview presented in this paper provides a useful framework to appreciate the general role of the cross sections driving event rates observed in the future.

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