Physics Letters B 748 (2015) 113–116

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

New physics with ultra-high-energy neutrinos

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ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form 30 June 2015
Accepted 1 July 2015
Available online 3 July 2015
Editor: S. Dodelson

ABSTRACT

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,[1] while the visible Cherenkov detector is IceCube and its expansion to Gen2 [11], 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. Ref. [12] was directed specifically to the IceCube configuration. The geometries of the balloon-borne ANITA and in-ice radio telescopes ARA/ARIANNA, and space-based EUSO make the analyses of the cross section dependence of their event rates quite subtle. Questions of when a detector ought to be treated as a planar detector or volume detector, or when events are earth-skimming or up-going, and even the effect of surface reflection for in-ice radio telescopes, come into play.

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 ~ 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

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[1] The possibility of a phased radio array deployed in glacial ice at Summit Station, Greenland with a PeV-scale threshold is under study [10].

http://dx.doi.org/10.1016/j.physletb.2015.07.002

Table 1
The cross section dependence of the up- and down-going neutrino event rates in the SM and in three new physics scenarios for surface/fluorescence and Cherenkov experiments. The symbol σ_τ^{SM} stands for the standard ν_τ-nucleon cross section. We consider neutrino energies above 100 PeV, so that the LPM suppression for ν_e showering in ice above $\sim$EeV and τ escape in air above ~ 100 EeV, have already occurred.

Experiment type	SM	New physics		
	σ^{SM}	$\sigma_{TOT} = \alpha\sigma_{TOT}^{SM}$	$\Delta\sigma_{NC} = \alpha\sigma_{NC}^{SM}$	$\sigma_{BH} = \alpha\sigma_{TOT}^{SM}$
Surface detector/fluorescence (in air):				
PAO/TA/EUSO (down)	σ_{sh}^{SM}	$\alpha\sigma_{sh}^{SM}$	$\sigma_{sh}^{SM} + <y> \Delta\sigma_{NC}$	$\sigma_{sh}^{SM} + \sigma_{BH}$
PAO/TA/EUSO[a] (up)	$\frac{\sigma_\tau^{SM}}{(\sigma_{att}^{SM})^2}$	$\frac{\alpha\sigma_\tau^{SM}}{(\alpha\sigma_{att}^{SM})^2}$	$\frac{\sigma_\tau^{SM}}{(\sigma_{att}^{SM}+<y>\Delta\sigma_{NC})^2}$	$\frac{\sigma_\tau^{SM}}{(\sigma_{att}^{SM}+\sigma_{BH})^2}$
Radio/visible Cherenkov (in ice):				
ANITA/ARA/ARIANNA/IceCube-Gen2 (down)	σ_{sh}^{SM}	$\alpha\sigma_{sh}^{SM}$	$\sigma_{sh}^{SM} + <y> \Delta\sigma_{NC}$	$\sigma_{sh}^{SM} + \sigma_{BH}$
ANITA/ARA/ARIANNA/IceCube-Gen2 (up)	$\frac{\sigma_{sh}^{SM}}{\sigma_{att}^{SM}}$	$\frac{\alpha\sigma_{sh}^{SM}}{\alpha\sigma_{att}^{SM}}$	$\frac{\sigma_{sh}^{SM}+<y>\Delta\sigma_{NC}}{\sigma_{att}^{SM}+<y>\Delta\sigma_{NC}}$	$\frac{\sigma_{sh}^{SM}+\sigma_{BH}}{\sigma_{att}^{SM}+\sigma_{BH}}$

[a] For EUSO, the inverse square dependence on the attenuation cross section is an idealization that is somewhat mitigated on detailed modeling [15].

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), one 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. [12], 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 $\alpha_{CC} \equiv \sigma_{CC}/\sigma_{TOT}^{SM}$ and $\alpha_{NC} \equiv \sigma_{NC}/\sigma_{TOT}^{SM}$, and parametrize a new completely inelastic cross section (also normalized to σ_{TOT}^{SM}) by α_{BH}. Then, for the SM, $(\alpha_{CC}, \alpha_{NC}, \alpha_{BH}) = (r_{CC}, r_{NC}, 0) \approx (0.71, 0.29, 0)$ [13], with $r_{CC} = \sigma_{CC}^{SM}/\sigma_{TOT}^{SM}$ and $r_{NC} = \sigma_{NC}^{SM}/\sigma_{TOT}^{SM}$. A scenario in which the total cross section is scaled by α, i.e., $\sigma_{TOT} = \alpha\sigma_{TOT}^{SM}$, is described by $(\alpha_{NC}, \alpha_{NC}, \alpha_{BH}) = (\alpha r_{CC}, \alpha r_{NC}, 0)$. 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}, α).[2] In what follows, we distinguish between the attenuation cross section, σ_{att}, which is relevant for up-going/skimming neutrinos, and the showering cross section, σ_{sh}. Note that σ_{sh}^{SM} is σ_{TOT}^{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 1.

The cross section weighted by inelasticity, called the attenuation cross section, for flavor f in the standard model can be written as [12],

$$\begin{aligned} \sigma_{att}^{SM f} &= \sigma_{CC}^{SM} + \sigma_{NC}^{SM} < y_{NC}^f > \\ &= \sigma_{CC}^{SM} + 0.2\sigma_{NC}^{SM} \\ &\simeq 0.77\sigma_{TOT}^{SM}. \end{aligned} \quad (1)$$

The attenuation cross sections are the same for the three neutrino flavors (labeled $f = e, \mu, \tau$) because $< y_{NC}^f > \simeq 0.2$ is the mean inelasticity factor for the NC cross section at energies above 100 PeV [13]. The final form in Eq. (1) results from the relation $\sigma_{CC}^{SM} \simeq 2.5\sigma_{NC}^{SM}$, independent of energy at UHE for a wide range of cross section estimates [13]. 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 $\sigma_{sh}^{SM} \simeq 0.21\,\sigma_{TOT}^{SM}$ for ν_e, ν_μ, and ν_τ, with additional contributions from the electromagnetic shower in the ν_e case, and from τ decay in matter in the ν_τ case, with each new contribution falling with energy. For the effective showering cross sections, factors like the Landau–Pomeranchuk–Migdal (LPM) effect [14] and the τ lifetime $(48\,(\frac{E_\tau}{\text{EeV}})$ km) introduce significant energy dependence into the inelasticity factors [2,4,6,7,9].

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 ($\sigma_{pN} \sim 100$ 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 [15]. The SM neutrino cross section at 10^{20} eV is 0.5×10^{-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 0.5×10^{-4}, and 6×10^{-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 ν_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.[3]

The ν_μ and ν_τ collisions, whether CC or NC, transfer only their hadronic recoil portion to showers. However, at energies below $10^{4.5}$ to 10^5 PeV, the τ produced in a CC ν_τ interaction decays quickly enough to provide a significant addition to the showers [16]. The detectability of NC events is suppressed because the NC cross section is 2/5 of the CC cross section, and NC events

[2] Note that in Ref. [12], the NC case is described by $(r_{CC}, r_{NC} + \alpha, 0)$ because there $\Delta\sigma_{NC} = \alpha\sigma_{TOT}^{SM}$.

[3] For detectors that rely on the radio Cherenkov radiation from showers in ice [5–7,9], the LPM effect causes electromagnetic shower elongation and fluctuation in shower maxima, which degrades the coherence of the signal. The result is that the dominant mode is tau decays into hadrons, for E_{ν_τ}'s above about 100 PeV. 100 PeV is the threshold for RICE, and about a factor of ten above the ARA threshold. The ANITA and ARIANNA thresholds are above an EeV, so the ν_e CC contribution is strongly suppressed and the hadronic tau decays are very dominant.

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 ν_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 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 emerging and showering via its decay [17]. Thus, up-going neutrinos effecting showers seen above the Earth are restricted to ν_τ's. Remarkably, the rate for up-going, Earth-skimming τ's from ν_τ CC scattering presents an observable signal [18]. In fact, the up-going rate scales roughly as $\sigma_\tau/\sigma_{\rm att}^2$, due to Earth-absorption effects [19]. The τ's, of course, emerge almost parallel to the ground. This reduced solid angle presents an additional penalty factor for PAO, TA and EUSO [19]. We add that the regeneration effect for ν_τ's results in a pile-up of ν_τ's at $\sim$ PeV [20], well below the energies of interest to us here. So we are justified in neglecting ν_τ regeneration.

For up-going PAO/TA/EUSO events, a tau lepton produced by an Earth-skimming neutrino collision must emerge into the atmosphere still carrying a substantial fraction of the neutrino energy in order to be detected as an UHE neutrino signal. The τ's relatively small rate of energy loss and short lifetime (2.9×10^{-13} s in its rest frame) allow for a significant chance for detection of its showering decay products by experiments like PAO, TA and EUSO. We remark that Earth-curvature effects [15] become important when the τ decay length cannot be ignored relative to the Earth's radius, i.e., when order $\frac{c\tau_\tau}{R_\oplus}\sim(\frac{E_\tau}{10\ \rm EeV})\times 7\%$ accuracy is required.

The upward solid angle available is limited by the ever shorter attenuation length $\lambda_{\rm att}$ as the energy grows. The maximum chord length for a neutrino entering the detector volume is $\sim\lambda_{\rm att}$, so the maximum solid angle is restricted to $2\pi\sin\theta_h$, where $\sin\theta_h=\lambda_{\rm att}/2R_\oplus$ is the angle between the entry direction and the horizon. Consequently there is a reduction factor of $\lambda_{\rm att}\sim 1/\sigma_{\rm att}$ in the expected acceptance. When the τ 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 $\sin\theta_h$ penalty factor, which shows up as the square in the denominators of the PAO/TA/EUSO "up" rows in Table 1.

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 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, $\lambda_{\rm att}\sim 1/\sigma_{\rm att}$. Moreover, Cherenkov detection is not limited to ν_τ 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 [12,15,16,19,21]. We have drawn on these sources for the comments made above, and summarize these comments in the "SM" column of Table 1.

Next we turn to the effects of possible new physics. The case of purely new NC physics, $\Delta\sigma_{\rm NC}$, adds $<y_{\rm NC}>\Delta\sigma_{\rm NC}$ 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

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

Because of the small inelasticity, it is seen that an enhancement of $1+\alpha\approx\frac{1}{<y_{\rm NC}>}\sim 5$ is needed to make $\sigma_{\rm att}^{\Delta\rm NC}$ comparable to $\sigma_{\rm TOT}^{\rm SM}$.

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 ν_e CC-initiated showers and τ decay showers up to 10 EeV, but above 100 EeV the τ showers are a few percent or less because the increased decay length carries the τ outside the observable atmospheric volume before it decays [15,16]. In Table 1, the cross section dependence for EUSO (down) under $\Delta\sigma_{\rm NC}$ is then $\sigma_{\rm CC}^{\rm SM}$ for flavors e and τ for neutrino energies up to $10^{4.5}$ PeV and for just e above that. The contribution of $\Delta\sigma_{\rm NC}$ will be small unless $\alpha\gtrsim 5$.

Similar considerations lead us to the entries in Table 1 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 ν_τ 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.

Acknowledgements

This work was supported by the DOE under Grant Nos. DE-SC0010504 and DE-SC0011981, and by the Kavli Institute for Theoretical Physics, Santa Barbara (NSF Grant No. PHY11-25915). T.J.W. is also supported by a Simons Foundation Grant, #306329.

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