Resonant Scattering and Charm Showers in Ultrahigh-Energy Neutrino Interactions

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Electron antineutrinos with energy $\sim 7\times 10^6$ GeV have much-enhanced cross sections due to W-boson production off electrons. Possible signals due to cosmic-ray sources are estimated. Higher-energy antineutrinos can efficiently produce a W accompanied by radiation. Another possibility, which could lead to shadowing at modest depths, is resonant production of a charged Higgs particle. The importance of muon production by charm showers in rock is pointed out.

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Recently there has been a resurgence of interest in ultrahigh-energy cosmic-ray neutrinos, stimulated in part by evidence that Cygnus X-3 is likely to be a potent source.[1] It seems appropriate in this context to note that incident electron antineutrinos with energy $\sim 7\times 10^6$ GeV have a much-enhanced interaction cross section as a result of s-channel resonant W production. The observation that such an enhancement exists is quite an old one[2]; my purpose here is to reexamine the situation with modern values for the theoretical and experimental parameters, which are quite different from the original guesses. The numerical results of this exercise appear to be not unpromising for possible future searches.

Let us begin by applying simple Breit-Wigner theory to the reaction $\bar{\nu}_e e \rightarrow W$. The total cross sections are, in standard notation, for s and p waves, respectively,

$$\sigma_s(\epsilon)=\frac{\pi}{k^2}\frac{\Gamma_{is}\Gamma_s}{(\epsilon-M)^2+(\Gamma/2)^2}, \quad (1a)$$

$$\sigma_p(\epsilon)=\frac{3\pi}{k^2}\frac{\Gamma_{ip}\Gamma_p}{(\epsilon-M)^2+(\Gamma/2)^2}. \quad (1b)$$

The various partial widths are related by

$$\Gamma_{is}/\Gamma_s=\Gamma_{ip}/\Gamma_p=1/f, \quad (2)$$

$$\Gamma=\Gamma_s+\Gamma_p=\tfrac{4}{3}\Gamma_s, \quad (3)$$

where f is the number of independent fermion channels; for a standard model with three families $f=12$. Equations (2) and (3) result from universality and from the spin-1 nature of the W, respectively. Adding together (1) and (2), with $k=40$ GeV ($M=80$ GeV) and $\Gamma=3$ GeV, and supplying a factor $\frac{1}{2}$ for unpolarized electrons, we find the peak cross section

$$\sigma_{\text{peak}}=1.5\times 10^{-31}\ \text{cm}^2. \quad (4)$$

This peak cross section translates into a penetration depth of approximately 40 km in rock of density 5 g/cm^3. Thus antineutrinos of this energy will be shadowed when the source is well below the horizon, but not at modest zenith angles even for the deepest available detectors.

Of almost equal importance is the reaction $\bar{\nu}+e \rightarrow W+\gamma$ at somewhat higher energies. The cross section for this, to logarithmic accuracy, is the peak cross section multiplied by $(\alpha/\pi)\ln(M^2/m^2)\simeq 0.06$. This value should obtain where the soft-photon approximation is adequate, i.e., $E_0 \lesssim E \lesssim 2E_0$.

We now pass from the cross section to event rates, given an estimated flux. Let us define $\phi(E)$ to be the flux of neutrinos at energy E. The center-of-mass energy ϵ is related to E by $\epsilon^2=2mE$, m being the electron mass. The energy E_0 necessary for W production off electrons at rest is

$$E_0=M^2/2m\simeq 7\times 10^6\ \text{GeV}. \quad (5)$$

Notice that the relatively modest spread in ϵ corresponding to the width of the W translates into a much larger spread in E. Integrating over the Breit-Wigner shape one finds the total rate per electron as

$$R=\phi(E_0)\frac{\sigma_{\text{peak}}}{m}\frac{\pi\Gamma}{2}M$$
$$=\phi(E_0)\times(1.2\times 10^{-25}\ \text{GeV}\cdot\text{cm}^2). \quad (6)$$

As a simple schematic model of what the flux from a source like Cygnus X-3 might be let us suppose that 10^{38} erg/sec are deposited in neutrinos with a flat spectrum extending to 10^7 GeV. This might be a first approximation to the expectation from Hillas's model[3] of the source, where the output of this source arises from impacts of 10^8-GeV protons on a tenuous atmosphere. In this model, taking 10 kpc as the distance we find for the total neutrino flux

$$\phi_t(E_0)=2\times\frac{10^{38}\ \text{erg/sec}}{(10^7\ \text{GeV})^2\times 10^{46}\ \text{cm}^2}$$
$$\simeq 1.2\times 10^{-19}/\text{GeV}\cdot\text{cm}^2\cdot\text{sec}. \quad (7)$$

The $\bar{\nu}_e$ component of this flux will be about $\frac{1}{6}$ if we assume no oscillation (see below), since $\bar{\nu}_e$ emerges from the chain $\pi\rightarrow\mu^-\bar{\nu}_\mu$, $\mu^-\rightarrow\nu_\mu e^-\bar{\nu}_e$, but not from π^+. Needless to say, this flux is uncertain by at least an order of magnitude.

Taking one-sixth of (7) and multipying by (6) we find a contained event rate in 10^{14} cm^3 of water (project DUMAND) of approximately 2/yr. A nearly equal contribution arises from the radiative process.

Penetrating muons can also be produced in rock. These will arise from two main processess: direct decay of the produced W or rapidly decaying secondary (t,b,τ), or decay of a c quark. The latter is a special case for two reasons. First, $c\bar{c}$ pairs might be expected to be fairly copiously produced in hadronic showers at the energies considered. Second, the scattering time for a strong collision of the c quark in rock is comparable to the time-dilated lifetime when $\gamma \simeq 10^4$; since higher-energy quarks will rapidly lose energy there is a cap on the energy (and hence the range) of muons arising this way.

The direct process is straightforward to analyze. Multiplying (6) and (7) by the number of electrons in a typical depth of 2 km, by $\frac{1}{6}$ for the $\bar{\nu}_e$ fraction, and by $\frac{1}{5}$ for the prompt muon output per W decay, one finds the μ flux as

$$\phi_\mu \simeq \frac{1}{5} \times R \times \frac{1}{6}\phi_t \left(2\times 10^{24}\ \frac{e}{\mathrm{cm}^3}\right) \times (2\times 10^5\ \mathrm{cm}) \simeq 1.6\times 10^{-16}/\mathrm{cm}^2\cdot\mathrm{sec}. \quad (8)$$

This flux should actually depend linearly on depth up to the penetration depth, which is ~ 5 km for a 10^3-TeV muon.

The process involving charm is more difficult to estimate but almost surely larger especially at modest depths. As a rough guide let us guess that a hadronic shower of 7×10^6 GeV in rock produces 25 $c\bar{c}$ pairs with energy $\gtrsim 10^3$ GeV. (Estimates of charm production of approximately $\frac{1}{10}$ per collision, compared to a total multiplicity of ~ 15, are believed to be conservative at ultrahigh energies.[4]) Decay of these will produce on the average 5 muons which penetrate about 1 km. Thus the rate of muon production is estimated at

$$\phi_\mu = 3\times 10^{-15}/\mathrm{cm}^2\cdot\mathrm{sec}, \quad (9)$$

through cascades initiated by resonant W production. Both (8) and (9) should be roughly doubled by the radiative processes.

If these figures are taken literally they indicate that the resonant process is only marginally detectable; anyone who has worked through the estimates will realize they are highly uncertain—if the flux turns out to be an order of magnitude higher, for example, the experimental prospects become quite bright.

We now collect some remarks of a more general nature:

(i) Resonant production as discussed here may be separated experimentally from nonresonant sources by the different depth dependence; i.e., shadowing of the resonant process.

(ii) Neutrino oscillations may significantly alter the ν_e/ν_μ ratio seen at earth from that emitted at the source. In this connection, note that for Cygnus X-3 there will be significant oscillations for neutrino $(\mathrm{mass})^2$ differences as small as

$$\delta m^2 \simeq l/E \simeq 5\times 10^{-2}\ \mathrm{eV}^2. \quad (10)$$

If we put together (i) and (ii), it may become possible to get some information on very small neutrino masses.

(iii) The production of secondary charmed particles in hadronic showers is likely to be a significant source of penetrating muons in a broader context. Even in ultrahigh-energy ν_μ collisions, it may well be the dominant source. The signal, of course, is multimuon events.

(iv) Production of a lighter particle[5]—for example, a charged scalar Higgs particle—with fewer channels could lead to a larger resonant cross section, and shadowing in smaller amounts of material. A cross section ~ 40 times as large as (3) would give us shadowing in ~ 1 km of rock, and might be consistent with the zenith-angle distribution reported by Marshak *et al.*[6]

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