Neutrino-Photon Reactions in Astrophysics and Cosmology

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At energies above the threshold for W production the process $\nu\gamma \rightarrow lW^+$ is competitive with $\nu\nu$ scattering at the same center of mass energies. In a cosmological setting, absorption of ultrahigh energy neutrinos by the microwave photon background is comparable to absorption by the neutrino background. In passing through matter, the process $\nu \rightarrow lW^+$ will occur in the Coulomb field of nuclei. For iron, the interaction rate per nucleon is roughly 20% of the charge current cross section. The related process $\overline{\nu}_e e^- \rightarrow \gamma W^-$ dominates $\overline{\nu}_e e^-$ scattering for about a decade in energy above the resonance for W production. [S0031-9007(97)05173-9]

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Neutrinos of very high energy have become a subject of some interest [1]. Detection of such neutrinos could provide a means of identifying and studying sources of the highest energy cosmic rays [2,3]. Neutrinos, γ rays, and nucleons are all produced at the source via hadronic reactions. Unlike photons or nucleons, however, neutrinos can both escape the central accelerator and propagate cosmological distances while preserving line of sight information to indicate the location of the source. High energy neutrinos from the decay or annihilation of particle dark matter [4] or from the decay of cosmic strings [5,6] could provide important clues for a deeper understanding of particle physics and/or cosmology. Recent models of γ-ray bursts may be testable by looking for coincident neutrinos with energies $E_\nu > 10^{14}$ eV [7].

With these thoughts in mind, experimental efforts are being initiated to detect cosmic neutrinos at energies from 10^{14} to 10^{20} eV either underwater [8,9], underice [10,11], or possibly in horizontal air showers at an intensive air shower array [6]. Detection of such high energy neutrinos could be a boon for particle physicists as well. It is expected that such neutrinos would be absorbed by the Earth. By measuring the flux as a function of nadir angle, one could measure neutrino-nucleon cross sections at high energies [12]. Such a measurement would supply information about nucleon structure functions at energies inaccessible to current accelerators.

In all these cases, estimates of neutrino reaction rates have been based upon the exchange of weak vector bosons with nucleons or electrons, or in the case of cosmological absorption [13–16], the cosmic neutrino background. Here it is pointed out that neutrino-photon reactions that produce final state "on shell" weak vector bosons should not be neglected. The photon can be real, as in $\nu\gamma \rightarrow lW^+$, or virtual, as in $\nu N \rightarrow NlW^+$ catalyzed by the Coulomb field of the nucleus. For the case of scattering from electrons, the photon may be in the final state, $\overline{\nu}_e e^- \rightarrow \gamma W^-$, which enhances $\overline{\nu}_e e^-$ scattering above the "Glashow resonance" for W production [17]. These three cases are presented below followed by a summary and discussion.

$\nu\gamma \rightarrow lW^+$. It is straightforward to calculate the cross section for $\nu\gamma \rightarrow lW^+$ using the standard model Lagrangian. A general form for the cross section is

$$d\sigma_{\nu\gamma\rightarrow lW^+} = |\mathcal{M}|^2 \delta^4(p_i - p_f)(2\pi)^4 \frac{1}{4I} d\rho_f\,, \quad (1)$$

where p_i and p_f denote initial and final particle four-momenta, ρ_f is the final particle phase space, I is the Lorentz invariant flux factor, and $\mathcal{M}$ is the Lorentz invariant amplitude for the process. Figure 1 shows the two diagrams that contribute to $\mathcal{M}$. For the present purposes it is sufficient to consider the cross section for unpolarized particles, so $|\mathcal{M}|^2$ may be simplified by summing over W polarizations, $\sum_{\lambda_W} \epsilon^\mu_{\lambda_W}\epsilon^\nu_{\lambda_W} = -(g^{\mu\nu} - \frac{p^\mu_W p^\nu_W}{M_W^2})$. Before performing a similar sum over photon polarizations, it is useful to calculate the electromagnetic current tensor $J_{\mu\nu} = J_\mu J_\nu$, where J is the current which couples to photons. The matrix element can then be written in the form $|\mathcal{M}|^2 = \epsilon^\mu\epsilon^\nu J_{\mu\nu}$, where ϵ is the photon polarization vector. For unpolarized photons one then uses the average $\frac{1}{2}\sum_\lambda \epsilon^\mu_\lambda\epsilon^\nu_\lambda = -\frac{1}{2}g^{\mu\nu}$. As a check of the algebra one can test that $p^\mu_\gamma J_{\mu\nu} = p^\nu_\gamma J_{\mu\nu} = 0$ which is demanded by gauge invariance. J is also useful for calculating $\nu N \rightarrow NlW^+$ in the nuclear Coulomb field.

Figure 2 shows the cross sections for $\nu\gamma \rightarrow lW^+$ for the three different neutrino flavors. Near threshold, the lepton propagator in Fig. 1(a) leads to a large logarithm which enhances the cross section for ν_e over that for ν_μ and ν_τ. Setting the lepton mass to zero everywhere but in the logarithm, the cross section is fairly compact:

$$\sigma_{\nu\gamma\rightarrow lW^+} = \sqrt{2}\alpha G_F\Bigg[2\left(1 - \frac{1}{y}\right)\left(1 + \frac{2}{y^2} - \frac{1}{y^2}\ln y\right) + \frac{1}{y}\left(1 - \frac{2}{y} + \frac{2}{y^2}\right) \times \ln\frac{m_W^2(y-1)^2}{m_l^2 y}\Bigg], \quad (2)$$

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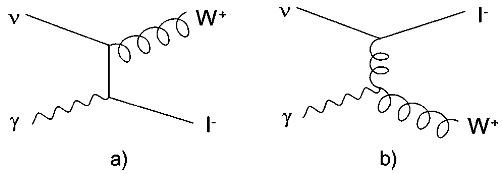

FIG. 1. Two amplitudes contributing to $\nu\gamma \rightarrow lW^+$: (a) is "Compton-like," while (b) involves a three-gauge coupling. Both must be included to maintain gauge invariance.

where $y = s/m_W^2$ and $s = (p_\nu + p_\gamma)^2$, G_F is Fermi's constant, and α is the fine structure constant which runs to $\sim 1/128$ near m_W.

One application of $\nu\gamma$ scattering is absorption of ultrahigh energy neutrinos off the microwave photon background. The potential importance of this process is illustrated in Fig. 3, where the $\nu_e\gamma$ cross sections is compared to relevant $\nu\nu$ and $\nu\overline{\nu}$ cross sections at the same center of mass energies [14]. The figure is dominated by processes involving intermediate Z bosons at resonance, but at higher energies the $\nu\gamma$ cross section is comparable or larger than that for the $\nu\nu$ reactions.

In a cosmological setting, the absorption rate is calculated by integrating the cross section over the distribution of the target species. There are six flavors of neutrino and several processes to sum over. On the other hand, photons have two spin degrees of freedom, and are more numerous than neutrinos by virtue of their higher temperature and boson statistics. Figure 4 shows the ratio of these absorption rates to that for cosmological expansion. Near the Z resonance, absorption is dominated by that process, but at higher energies $\nu\gamma$ is important. Above the Z resonance the $\nu\nu$ processes mostly result in charged and neutral leptons, whereas the $\nu\gamma$ process produces W^+ bosons which mostly decay to quarks. Thus, not only is the amplitude of the absorption modified, but also the character of the cascade products.

In the present epoch the $\nu\gamma$ process is important only for neutrinos with energies $E_\nu > 10^{16}$ GeV, and

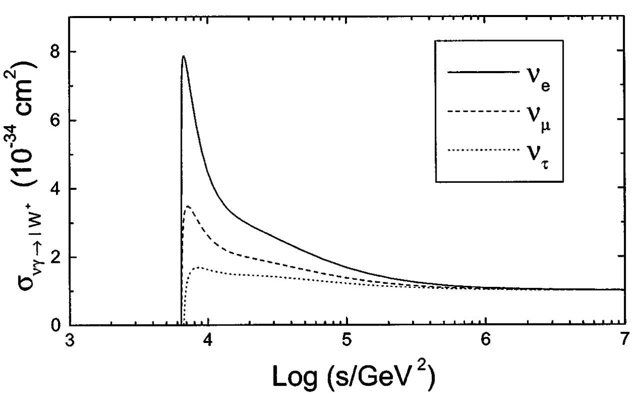

FIG. 2. Cross section for $\nu\gamma \rightarrow lW^+$ for three flavors of neutrino as a function of s the squared center of mass energy. The threshold is at $s = (m_W + m_l)^2$.

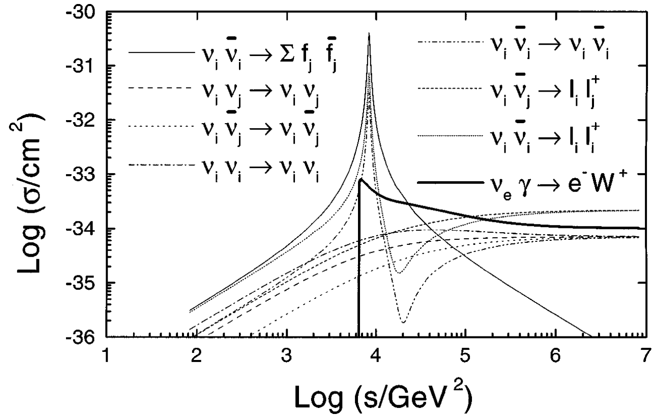

FIG. 3. Comparison of the $\nu_e\gamma$ cross section to that for various $\nu\nu$ and $\nu\overline{\nu}$ processes as a function of s. The sum $\sum_j f_j \overline{f}_j$ does not include $f_j = \nu_i, l_i, t, W,$ or Z.

even then only a fraction of the beam is absorbed. Pushing back, neutrinos produced with energy $E_\nu(1 + z) > 10^{16}$ GeV at redshifts $(1 + z) > 10$ would have been absorbed in their production epoch. A full cascade calculation must be done [16], evolving the ultrahigh energy neutrino distribution to lower energies where they can propagate to the present unabsorbed. That cascade will be somewhat modified by the inclusion of $\nu\gamma$ reactions.

$\nu N \rightarrow NlW^+$. In addition to reactions with real photons, it is also possible to convert $\nu \rightarrow lW^+$ in an external electromagnetic field. The most obvious case to consider is the Coulomb field of a nucleus, where both significant field strength and momentum transfer are possible.

In the rest frame of the target nucleus, the cross section per nucleon can be expressed as a convolution

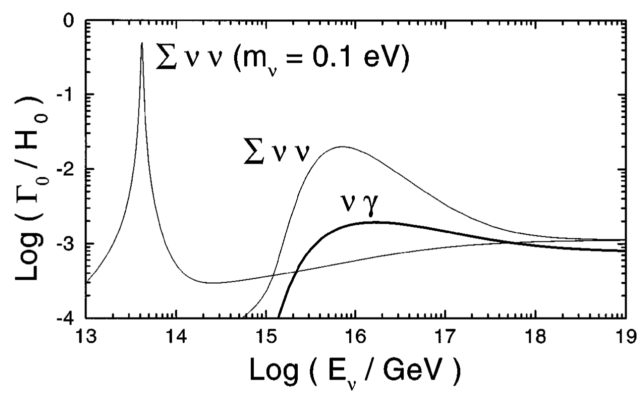

FIG. 4. The ratio of absorption of high energy neutrinos by the cosmic background of photons and neutrinos to the cosmic expansion rate. [$H_0 = 50$ (km/sec)/Mpc, $T_\gamma = 2.74$ K, and $T_\nu = (4/11)^{1/3} T_\gamma$.] The light lines show absorption by neutrinos when (i) all neutrinos have $m_\nu = 0$ or (ii) the absorbed flavor has $m_\nu = 0.1$ eV, but the other flavors are massless. These curves include a sum over the processes in Fig. 3. Absorption by γ's is slightly subdominant to case (i), but for case (ii) the Z resonance is shifted to lower energy and the $\nu\gamma$ process prevails for over two decades in E_ν.

over scattering of the neutrino with the virtual photons in the Coulomb field.

$$d\sigma_{\nu N\to NlW^+} = d\sigma' \frac{I'}{I} \frac{Z^2 e^2 m_N^2 F_N^2(\mathbf{q}^2)}{A\mathbf{q}^4} \frac{d^3\mathbf{q}}{(2\pi)^3 2m_N}, \quad (3)$$

where $d\sigma'$ is as in Eq. (1) except that the real photon is replaced by a virtual photon of momentum $\mathbf{q}$ and polarization j_N^μ/m_N. Here the electromagnetic current of the nucleus is defined as eZj_N^μ. In the rest frame of the nucleus, the matrix element used in $d\sigma'$ is $|\mathcal{M}'|^2 = 4J_{00}$, since in this frame $p_N^\mu = m_N\delta^{\mu 0}$ and we use $q^\mu J_\mu = 0$ [18]. In Eq. (3) the quantity I refers to the νN system and I' refers to the ν-virtual γ system, so that $I'/I = \mathbf{q}z/m_N$, where z is the direction cosine between the incident neutrino and $\mathbf{q}$, Z and A are the charge and atomic number of the nucleus, and F_N is the form factor of the nucleus normalized to $F_N(0) = 1$. J_{00} can then be expanded in powers of $\mathbf{q}^2/m_W^2$, taking care to keep terms of order $E_\nu^2\mathbf{q}^2/m_W^4$ until after the $d^3\mathbf{q}$ integration is done. In this expansion, m_e may be safely set to zero as the logarithm associated with the intermediate lepton is cut off by $\mathbf{q}^2$, which is generally larger than m_e^2. For ν_μ and ν_τ conversion, the lepton mass should be kept.

The highest momentum components of the nuclear field establish the threshold for conversion. These have momenta of roughly 100 MeV, so that $\nu N \to NlW^+$ has a threshold of $E_\nu \approx 10^{14}$ eV. This is an interesting range for current and proposed underwater/ice neutrino detectors. Figure 5 shows the ratio of the cross section per nucleon for $\nu_e N \to NeW^+$ to that for charged current interactions [12] for the cases where the nuclear target is oxygen and iron, as a function of neutrino energy. The case of oxygen is interesting for neutrino detection rates in water (or ice) which are seen to increase by some 10% at $E_\nu \approx 1$ Pev. The cross sections on iron are increased by 20–25%, which will have an impact on studies of nucleon structure functions based on absorption of high energy cosmic neutrinos by the Earth. At higher energies, the charged current cross section increases roughly as $E_\nu^{0.4}$ [12], whereas the photon exchange process increases only logarithmically and becomes less important.

That the Coulomb process is comparable to $\sigma_{\nu N,cc}$ is understandable from a parton viewpoint. The momenta of the "partons" is similar (100 MeV photons vs 300 MeV quarks). The number densities are similar, as long as the nuclear field is coherent. The parton cross sections are also similar, both being tree-level processes.

$\overline{\nu}_e e^- \to \gamma W^-$. Neutrino interactions in matter are usually dominated by scattering with nucleons. An exception is the case of $\overline{\nu}_e$: the s-channel reaction $\overline{\nu}_e e^- \to W^- \to f\overline{f}'$ is important near the W resonance, although it decreases in importance at higher energy. Instead of the reaction with final state fermions $f\overline{f}'$, it is also possible to produce on-shell W's accompanied by photons [19], $\overline{\nu}_e e^- \to \gamma W^-$, which is just the cross channel of the $\nu_e\gamma \to e^- W^+$ reaction considered above. As long as one does not work too close to the resonance, the cross section involves only the two diagrams related to those in Fig. 1. Dropping m_e except in the logarithm, the result is

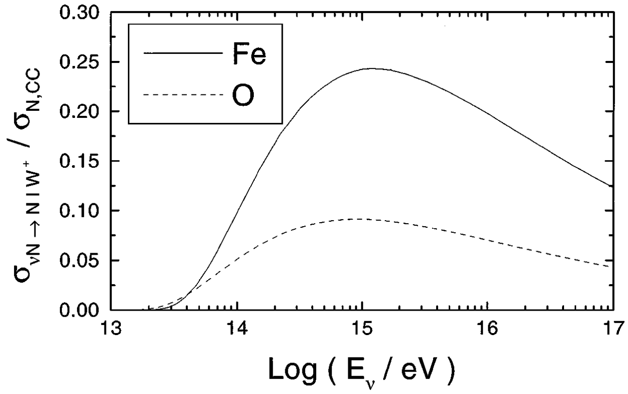

FIG. 5. Ratio of $\sigma_{\nu_e N\to NeW^+}$ to that for $\sigma_{\nu N,cc}$. The cross sections are per nucleon.

$$\sigma_{\overline{\nu}_e e^-\to\gamma W^-} = \frac{\sqrt{2}\alpha G_F}{3(y-1)y^2} \times \left[3(y^2+1)\ln\left(\frac{ym_W^2}{m_e^2}\right) - (5y^2+2y+5)\right], \quad (4)$$

where $y = s/m_W^2$ and here $s = 2m_e E_\nu$.

One might expect that with but a single channel and the smaller electromagnetic coupling that the γW^- reaction would be less important than $f\overline{f}'$ which proceeds to nine final states (12 above the top threshold). For very forward scattering, however, the $\overline{\nu}_e e^- \to \gamma W^-$ process involves the t-channel exchange of an almost on-shell electron, which leads to an enhancement by $\ln s/m_e^2 \approx 25$. As a result the γW^- rate exceeds the s-channel rate to $f\overline{f}'$ summed over all species, as can be seen in Fig. 6; i.e., the cross section for $\overline{\nu}_e e^- \to \gamma f\overline{f}'$ exceeds that for $\overline{\nu}_e e^- \to f\overline{f}'$.

At high energies, t-channel Z-boson exchange allows the elastic channel to dominate so the importance of γW^- decreases. For energies within a decay width of the resonance, a simple separation of the two processes is not possible—the photon is soft and so interference with initial and final state bremstrahlung emission must be considered [20]. For energies outside the width of the resonance, the photon produced in $\overline{\nu}_e e^- \to \gamma W^-$ is hard and so will not interfere with bremstrahlung.

In summary, neutrinos are generally considered to be weakly interacting particles, and thus neutrino-photon interactions are generally ignored, or confined to discussions of loop effects in scattering [21] or generating neutrino magnetic moments [22]. Here it is noted that for center of mass energies sufficient to produce real W bosons that

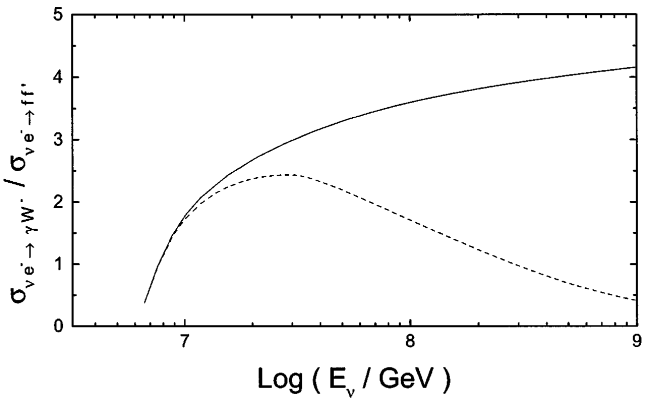

FIG. 6. Ratio of the cross section for $\overline{\nu}_e e^- \to \gamma W^-$ to that for $\overline{\nu}_e e^- \to f\overline{f}'$. For the solid curve the sum over $f\overline{f}'$ includes only the s-channel to final states open in W decay. The dashed curve includes the $b\overline{t}$ final state as well as the t-channel Z exchange for elastic scattering. Bosonic final states, e.g., $\nu e^- \to W^- Z$, are not included.

neutrinos and photons engage in $2 \to 2$ scattering at tree level via lepton exchange and through W exchange and a γWW vertex. The resultant $\nu\gamma$ reactions are competitive with traditional neutrino reactions at high energies and in some cases may be dominant.

Three examples have been explored: (a) $\nu\gamma \to lW^+$ is an important contribution to ultrahigh energy neutrino absorption in the early Universe, (b) $\nu N \to NlW^+$ catalyzed by the nuclear Coulomb field enhances νN reaction rates by 10–20% at neutrino energies of order 10^{15} eV, a range of interest to the next generation of neutrino telescopes, and (c) the tree-level process $\overline{\nu}_e e^- \to \gamma W^-$ is the dominant reaction in $\overline{\nu}_e e^-$ scattering for about a decade in E_ν just above the W resonance.

The current discussion has been confined to real W production, but it should be apparent that neutrino-photon processes may also occur below threshold. Here, however, the virtual W must decay, which results in two suppressions: the final state will have three particles instead of two, reducing the available phase space by about a factor of 100; and the decay vertex contains two powers of the weak coupling constant, a further reduction by about a factor of 10. In a cosmological setting the process $\nu\gamma \to lf\overline{f}'$ would therefore be expected to be about a factor of 1000 smaller than corresponding $\nu\nu$ scattering.

More interesting is the possibility of $\nu N \to Nlf\overline{f}'$ proceeding in the field of a nucleus. Even considering the Z^2 enhancement of the cross section, the cross section should be much reduced compared to the νN charge exchange cross section. However, for an experiment such as the detection of solar neutrinos at Kamiokande [23] the relevant comparison is to νe elastic scattering which is also suppressed relative to νN scattering so it is unclear if "Coulomb" scattering of neutrinos is unimportant. At slightly higher energies, even a modest contribution to νN scattering in the few hundred MeV range could change interpretations of the atmospheric neutrino anomaly [24].

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