The Implications of $\bar{\nu}_e e^- \rightarrow W^- \gamma$ for the Detection of High-Energy $\bar{\nu}_e$

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Abstract

We discuss some motivations for detecting high-energy neutrinos through the pure electroweak processes such as $\bar{\nu}_e e^- \rightarrow W^-$ and $\bar{\nu}_e e^- \rightarrow W^- \gamma$. We argue that the latter process can be viewed as an enhancement to the former one. The event-rate enhancement is estimated.

1. Introduction

An observation of high-energy neutrinos beyond the atmospheric background will mark the beginning of high-energy neutrino astronomy. Several high-energy neutrino detectors, commonly known as high-energy neutrino telescopes, are currently in an advanced stage of their deployments. These detectors operate according to the high-energy neutrino interactions, particularly those occurring inside the high-energy neutrino telescopes. The studies facilitated by the high-energy neutrino telescopes will complement the high-energy gamma ray astronomy for understanding the origin of cosmic high-energy radiation [1].

In this talk, we shall discuss some motivations for detecting the high-energy neutrinos through the pure electroweak interactions. In particular, we focus on the resonant absorption process $\bar{\nu}_e e^- \rightarrow W^-$ ($\rightarrow \bar{\nu}_\mu \mu^-$), now referred to as Glashow resonance [2, 3] and the scattering process $\bar{\nu}_e e^- \rightarrow W^- \gamma$ [4]. The role of the latter process will be discussed.

2. The Detection Modes of High-Energy Neutrinos

The typical detection of high-energy neutrinos is through the charged-current neutrino-nucleon scattering $\nu_l(\bar{\nu}_l) + N \rightarrow l^- (\bar{l}^+) + X$. For $10^7 \text{GeV} < E_\nu < 10^{12} \text{GeV}$, the cross section of this process can be parameterized as $\sigma^{CC}(\nu N) = 5.5 \cdot 10^{-36} \text{cm}^2 (E_\nu/1 \text{ GeV})^{0.363}$ [3]. In general, the cross section of neutrino-lepton scattering is suppressed except for the $\bar{\nu}_e e^-$ scattering at the resonance energy $E_{\bar{\nu}_e} = 6.3 \cdot 10^6 \text{ GeV}$. At this energy, the resonant absorption $\bar{\nu}_e e^- \rightarrow W^- \rightarrow \cdots$
hadrons occurs with a peak cross section \( \sigma^{\text{res}}(s = m_W^2) = 0.3 \text{ \( \mu b \)}. \) Although the resonant peak spreads only over the \( W \)-boson width, the overall event rate in the high-energy neutrino telescope is non-negligible after convoluting the absorption cross section with the incoming neutrino flux\(^5\).

It is interesting to note that the signature of \( \bar{\nu}_e e^− \rightarrow W^− \gamma \) is similar to that of the resonant absorption provided the outgoing photon is soft. If the photon is hard, one might be able to separate this process from the resonant absorption by detecting the hard photon. There are a few reasons for identifying the resonant absorption and \( \bar{\nu}_e e^− \rightarrow W^− \gamma \) processes in the high-energy neutrino telescopes. First of all, unlike the neutrino-nucleon scattering, the resonant absorption and \( \bar{\nu}_e e^− \rightarrow W^− \gamma \) do not contain any hadronic uncertainties. Therefore, they can be used to probe the absolute flux of \( \bar{\nu}_e \). Secondly, the \( \bar{\nu}_e \) flux measured in the high-energy neutrino telescope is in fact identical to the intrinsic \( \bar{\nu}_e \) flux from a cosmologically distant source, in spite of the flavor oscillations taking place between the source and the high-energy neutrino telescope\(^6\). Finally, we should point out that only the \( \bar{\nu}_e \) flux near the energy \( E_{\bar{\nu}_e} = 6.3 \cdot 10^6 \text{ GeV} \) can be probed by the resonant absorption and \( \bar{\nu}_e e^− \rightarrow W^− \gamma \). For other neutrino energies, the cross section of neutrino-nucleon scattering dominates.

### 3. Results and Discussion

The cross sections for resonant absorption and \( \bar{\nu}_e e^− \rightarrow W^− \gamma \) are both well known. We have further calculated the photon spectrum of the latter process\(^7\):

\[
\frac{d\sigma}{dy} = A(\lambda) \left[ \frac{1}{\lambda - 1} \frac{(\lambda^2 + 1)}{\lambda} y^{-1} + 4 \frac{\lambda^2 (\lambda - 1)}{\lambda} y - 2 \lambda^3 y^2 - \lambda (3 \lambda^2 - 4 \lambda + 3) \right],
\]

where \( A(\lambda) = \sqrt{2} \alpha G_F / (\lambda^2 (\lambda - 1)^2) \), with \( \lambda = s/m_W^2 \) and \( y = E_\gamma / E_{\bar{\nu}_e} \). The appearance of \( 1/y \) term in the spectrum \( d\sigma/\,dy \) indicates that the outgoing photon tends to be soft. Indeed, we have computed \( \langle y \rangle \), the average value of \( y \), for different incoming neutrino energies. We have found \( \langle y \rangle \simeq 1.3 \cdot 10^{-3} \) for \( E_{\bar{\nu}_e} = 6.6 \cdot 10^6 \text{ GeV} \), \( \langle y \rangle \simeq 6.0 \cdot 10^{-3} \) for \( E_{\bar{\nu}_e} = 8.6 \cdot 10^6 \text{ GeV} \), whereas \( \langle y \rangle \simeq 9.7 \cdot 10^{-2} \) for \( E_{\bar{\nu}_e} = 1.1 \cdot 10^7 \text{ GeV} \). The corresponding averaged photon energies in these cases are \( 8.6 \cdot 10^3 \text{ GeV} \), \( 4.1 \cdot 10^4 \text{ GeV} \), and \( 10^6 \text{ GeV} \) respectively. With the above energies, the photon radiation length is about 30 cm in the water or ice\(^8\). It turns out that the detection of such photons is impractical given the large separation of photomultiplier tubes in the current design of high-energy neutrino telescopes.

Without detecting the outgoing photon in \( \bar{\nu}_e e^− \rightarrow W^− \gamma \), one should treat this process as an enhancement to the resonant absorption. It is important to compare \( \bar{\nu}_e e^− \rightarrow W^− \gamma \) cross section with those of conventional channels. The behaviors of these cross sections as functions of \( E_{\bar{\nu}_e} \) are shown in Fig. 1.
Fig. 1. High-energy $\bar{\nu}_e$ absorption cross section $\sigma$ (cm$^2$), over two different target particles as a function of electron anti-neutrino energy $E_{\bar{\nu}_e}$ (GeV). The minimum value of $E_{\bar{\nu}_e}$ corresponds to $(M_W + \Gamma_W)^2/2m_e$.

In this figure, we have included, besides the cross section of the current process, the resonant cross section, $\sigma_{\bar{\nu}_ee^{-}\rightarrow W^{-}\text{hadrons}}$, taken from Ref. [9], as well as the charged current deep-inelastic $\bar{\nu}_e$ scattering cross section over nuclei, $\sigma_{\bar{\nu}_eN\rightarrow e^+X}$, taken from Ref. [5] with CTEQ4-DIS parton distribution functions. From Fig. 1, we note that $\sigma_{\bar{\nu}_ee^{-}\rightarrow W^{-}\gamma}$ dominates over the other two for less than half an order of magnitude in $E_{\bar{\nu}_e}$ ($7 \cdot 10^6 \leq E_{\bar{\nu}_e}/\text{GeV} \leq 1 \cdot 10^7$). The dominance is however within a factor of 2.

In Ref. [9], the hadron shower event rate due to the Glashow resonance formation in the $\bar{\nu}_ee^{-}$ scattering was estimated. We have computed an enhancement to this event rate by incorporating the contribution of $\bar{\nu}_ee^{-}\rightarrow W^{-}\gamma$ (see Fig. 1). The enhancement is typically about 10%. This enhancement, if become measurable, can be considered as a signature of hard photon emission in the absorption process $\bar{\nu}_e e^{-}\rightarrow W^{-}\gamma$ in a high-energy neutrino telescope. In this estimate, we have used the $dN/dE_{\bar{\nu}_e}$ given by

$$\frac{dN}{dE_{\bar{\nu}_e}} \approx 10^{-8} \left( \frac{E_{\bar{\nu}_e}}{1\text{GeV}} \right)^{-2} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1},$$

for the relevant $E_{\bar{\nu}_e}$ range. In Eq. (2), the $dN/dE_{\bar{\nu}_e}$ is the downward going differential $\bar{\nu}_e$ flux arriving at the high-energy neutrino telescope. Briefly, it is for the gamma ray burst fireball model proposed in Ref. [10], where $p\gamma$ interactions are suggested to produce the high-energy $\bar{\nu}_e$ flux at the gamma ray burst fireball
In conclusion, we have provided some motivations for detecting the high-energy $\bar{\nu}_e$ through the resonant absorption process $\bar{\nu}_e e^- \rightarrow W^-$ and the scattering $\bar{\nu}_e e^- \rightarrow W^- \gamma$, which are purely electroweak in nature. The latter process is shown to enhance the event rate of the former process by about 10%.

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