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The Glashow resonance in neutrino–photon scattering

I. Alikhanov

Institute for Nuclear Research of the Russian Academy of Sciences, 60-th October Anniversary Pr. 7a, Moscow 117312, Russia

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ABSTRACT

Reactions $\nu_l\gamma \to W^+l^-$ $(l = e, \mu, \tau)$ near the threshold $\sqrt{s} = m_W + m_l$ are analyzed. Two independent calculations of the corresponding cross sections (straightforward calculations using the Standard Electroweak Lagrangian and calculations in the framework of the parton model) are compared. It is shown that the Standard Electroweak Theory strongly suggests that these reactions proceed via the Glashow resonances. Accordingly, a hypothesis that the on-shell W bosons in the reactions $\nu_l\gamma \to W^+l^-$ are the Glashow resonances is put forward. A role of these reactions for testing T symmetry is discussed. A model with T-violating Glashow resonances for description of the distribution of the TeV–PeV neutrino events recently observed by the IceCube Collaboration is presented.

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1. Introduction

In the past few decades neutrino–photon reactions as well as their implications for astrophysics and cosmology have attracted some interest and a definite progress has been reached in this field [1–15]. For example, it has been realized that the inelastic process $\nu\gamma \to \nu\gamma\gamma$ significantly dominates over elastic scattering $\nu\gamma \to \nu\gamma$ [16–19]. In its turn, when the energy threshold of the electron–positron pair production is crossed, the reaction $\nu\gamma \to \nu e^+e^-$ becomes the dominant one [20].

Though neutrinos are generally considered to be weakly interacting particles, it has been shown that neutrino–photon interactions should not be confined only to discussions of loop effects in scattering, or generating neutrino magnetic moments [21]. In some cases $\nu\gamma$ reactions at tree level are competitive with the standard charged or neutral current neutrino scattering, and even may be dominant. An intuitive view of how a neutrino interacts with the photon is provided by the parton model [22,23].

With the completion of the IceCube kilometer-scale neutrino detector located at the South Pole [24], the idea of observing cosmic ultra-high energy (UHE) electron antineutrinos through the resonant s-channel reaction $\bar{\nu}_e e^- \to W^-$ [25,26] (the so-called Glashow resonance) is again in the focus of attention of physicists [27–32]. Moreover, there has already been a proposal to interpret the PeV cascade events (≈ 1.04 PeV, ≈ 1.14 PeV, ≈ 2.00 PeV) recently reported by the IceCube experiment [33–35] in terms of the Glashow resonance [36,37]. However, the antineutrino energy in the laboratory reference frame required to excite this resonance is $E_{\bar{\nu}} \approx m_W^2/(2m_e) = 6.3$ PeV (1 PeV $= 10^{15}$ eV), so that the gaps in energy between the observed events and the expected resonance position are of the order of a few PeV. It should be noticed that according to [34], the IceCube event reconstructed energy is not due to the resonance at 6.3 PeV at 68% C.L.

Usually in the analysis of UHE neutrino interactions, under the Glashow resonance the following reaction at $\sqrt{s} = m_W$ is implied:

$$\bar{\nu}_e e^- \to W^-, \tag{1}$$

though it would also be fair to refer to the remainder five similar processes predicted by the Standard Electroweak Theory,

$$\begin{aligned} &\nu_e e^+ \to W^+, \\ &\nu_l l^+ \to W^+, \\ &\bar{\nu}_l l^- \to W^-, \end{aligned} \tag{2}$$

as to the Glashow resonances ($l = \mu, \tau$). We do so in the subsequent discussion and call any of the reactions (1)–(2) the Glashow resonance.

The reason for highlighting (1) and ignoring (2) in the literature is simply that electrons as targets are explicitly present in matter while positrons, muons and tau leptons are not. Nevertheless, we would like to remind us that one can attribute an equivalent lepton spectrum to the photon as well as to charged particles [38]. Neutrinos may excite the Glashow Resonances on such equivalent leptons generated by atomic nuclei [22], so that the corresponding

E-mail address: ialspbu@gmail.com.

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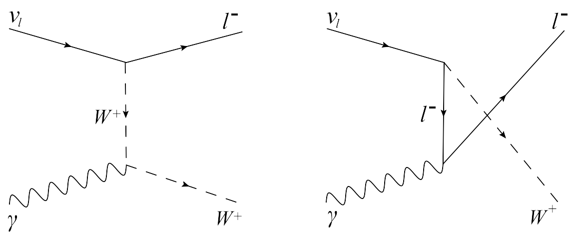

Fig. 1. Diagrams that contribute to the amplitude for $\nu_l\gamma \to W^+l^-$ at leading order [21].

probabilities should be studied in detail. We also emphasize that so far none of the Glashow resonances has been revealed and their experimental observation would undoubtedly be a crucial test of the Standard Electroweak Theory.

In the present paper we analyze the reactions

$$\nu_l\gamma \to W^+l^- \quad (l = e, \mu, \tau) \tag{3}$$

near the threshold $\sqrt{s} = m_W + m_l$ [21]. (Our conclusions are exactly the same for the CP conjugate reactions $\bar{\nu}_l\gamma \to W^-l^+$ since the equivalent lepton spectrum of the photon is CP-symmetric, but for the sake of definiteness we restrict attention to (3)).

We compare two independent calculations of the corresponding cross sections: 1) direct calculations using the Standard Electroweak Lagrangian [21]; 2) calculations in the framework of the equivalent particle approximation. We show that the Standard Electroweak Theory strongly suggests that the reactions (3) proceed via the Glashow resonances. Accordingly, we put forward a hypothesis that *the on-shell W bosons in the reactions* $\nu_l\gamma \to W^+l^-$ *are the Glashow resonances*.

If the hypothesis is true, then the mentioned reactions provide an opportunity to observe the Glashow resonances for all neutrino flavors at laboratory energies far below 6.3 PeV. For example, we have found that in the reactions $\nu_l{}^{16}\mathrm{O} \to {}^{16}\mathrm{O}W^+l^-$, relevant for the IceCube experiment, the Glashow resonances can appear already at neutrino energies about 20 TeV.

A role of these reactions for testing T symmetry at the IceCube Neutrino Observatory is discussed. We show that a model of T-violating Glashow resonance production by neutrinos interacting with the equivalent photons of the ^{16}O nuclei is able to describe the TeV–PeV neutrino events recently observed by the IceCube Collaboration [34].

2. Initial state lepton-strahlung mechanism for $\nu_l\gamma \to W^+l^-$

The cross sections of the reactions (3) can be straightforwardly calculated using the Standard Electroweak Lagrangian [21]. The two diagrams that contribute to the amplitude at leading order are depicted in Fig. 1. The result reads

$$\sigma_l = \sqrt{2}\alpha G_F\Big[2(1-\tau)\big(1+2\tau^2+\tau^2\log\tau\big) + \tau\big(1-2\tau+2\tau^2\big)\log\Big(\frac{m_W^2}{m_l^2}\frac{(1-\tau)^2}{\tau}\Big)\Big], \tag{4}$$

where $\tau = m_W^2/s$ and $s = (p_\nu + p_\gamma)^2$, G_F is the Fermi constant, and α is the fine structure constant. Fig. 2 shows the cross sections for the three different neutrino flavors.

One may notice the sharp rise of the cross sections at $\sqrt{s} \approx m_W + m_l$ (especially for ν_e) and the subsequent slow falling with energy. This is typical for processes in which the so-called initial state radiation takes place. It is well known that emission of real or virtual photons from the initial colliding electrons essentially modify the shapes of the narrow resonance curves [39]: the

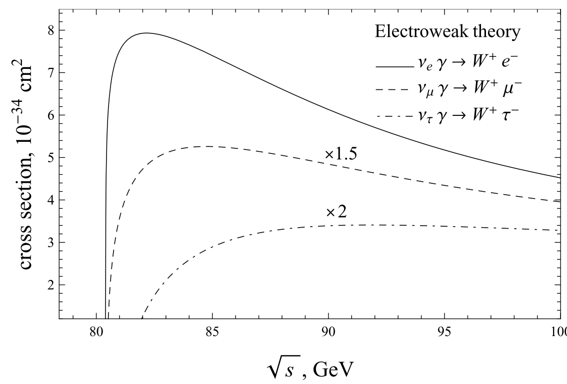

Fig. 2. Cross sections for $\nu_l\gamma \to W^+l^-$ as functions of the center-of-mass energy $\sqrt{s}$ straightforwardly calculated in the Standard Electroweak Theory [21].

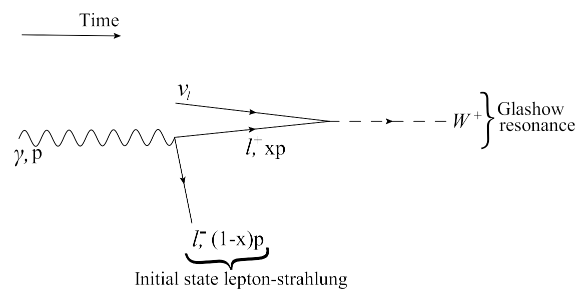

Fig. 3. A schematic illustration of the initial state lepton-strahlung mechanism of Glashow resonance production in $\nu_l\gamma \to W^+l^-$. The photon with a four-momentum p splits into a l^+l^- lepton pair before the Glashow resonance emerges (x is the fraction of the parent photon's momentum carried by the positively charged lepton). Even if the center-of-mass energy of the $\nu_l\gamma$ collision $\sqrt{s}$ exceeds the mass of the resonance m_W, the radiated l^- carries away the energy excess $(1-x)s = s - m_W^2$ and turns back the $\nu_l l^+$ pair to the resonance pole $xs = m_W^2$.

curves become wider, a suppression of the resonance maximum is observed and the main distinctive feature – *the radiation tail* – appears to the right of the resonance pole. The matter is that even if the collision energy $\sqrt{s}$ exceeds the mass of the resonance m_R, the radiated photon carries away the energy excess $E_\gamma = \sqrt{s} - m_R$ before e^+e^- annihilation and thus turns back the e^+e^- pair to the resonance energy.

Analogously, it is tempting to identify the shapes of the cross sections in Fig. 2 with the radiation tails arising due to initial state emission of charged leptons from the photon (initial state lepton-strahlung). In order to do this, we have to assume the following mechanism for the reactions (3) schematically illustrated in Fig. 3: the initial photon splits into a l^+l^- pair and subsequently the positively charged lepton from this pair annihilates with the ingoing neutrino into W^+ (the Glashow resonance), while the energy excess $\sqrt{s} - m_W$ is carried away by the outgoing l^-.

In addition to the peculiarities of the behavior of the cross sections near and above the threshold, there is also another argument strongly suggesting the initial state lepton-strahlung mechanism for $\nu_l\gamma \to W^+l^-$. Let us plot the QED structure functions of the photon, $F_2^{\gamma/l}(x,s)$, in a graph with flipped abscissa (recall that $F_2^{\gamma/l}(x,s)/x$ gives the probability density of finding a charged lepton in the photon with fraction x of the parent photon's momentum). When looking at such a graph shown in Fig. 4, one immediately recognizes the similarity to the shapes of cross sections from Fig. 3. It should be emphasized that the structure functions are obtained independently for deep inelastic charged lepton–photon scattering [40]. An explanation for this similarity is that the relatively narrow Glashow resonances project out the structure func-

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