The Glashow resonance in neutrino–photon scattering

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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. Predictions for the Glashow resonance production by high energy neutrinos in the IceCube detector are made.

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, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 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, 17, 18, 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, 28, 29, 30, 31, 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, 34, 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:

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

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

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

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

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

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 $\nu_l{}^{16}O \to {}^{16}O W^+ l^-$, relevant for the IceCube experiment, the Glashow resonances can appear already at neutrino energies about 10 TeV.

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

The cross sections for the reactions (3) can be straightforwardly calculated using the Standard Electroweak Lagrangian. The result reads [21]

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

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. Figure 1 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
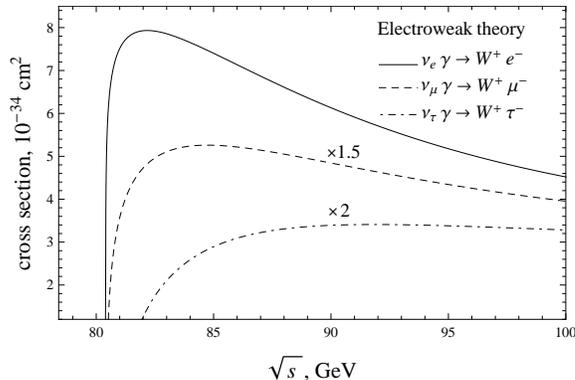
Figure 1: Cross sections for $\nu_l\gamma \to W^+l^-$ as functions of the center-of-mass energy $\sqrt{s}$ straightforwardly calculated in the Standard Electroweak Theory [21].
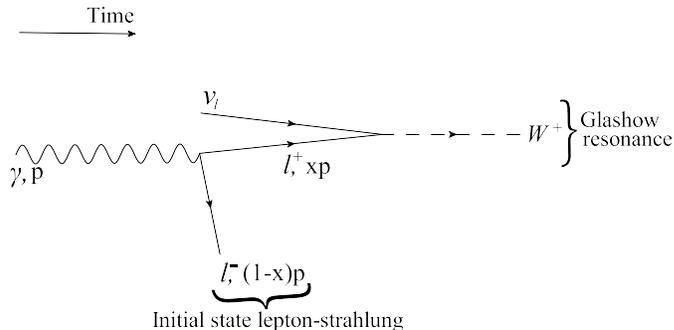

Figure 2: A schematic illustration of the initial state lepton emission mechanism for Glashow resonance production in $\nu_l\gamma \to W^+l^-$. The photon with a four-momentum p splits into a l^+l^- lepton pair before the Glashow resonance emerges (x is the fraction of the parent photon's momentum carried 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 $E = \sqrt{s} - m_W$ and turns back the $\nu_l l^+$ pair to the resonance pole $xs = m_W^2$.

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 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. 1 with the radiation tails arising due to the initial state emission of charged leptons from the photon. In order to do this, we have to assume the following mechanism for the reactions (3) schematically illustrated in Fig 2: 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 charged lepton emission 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. 3, one immediately recognizes the similarity to the
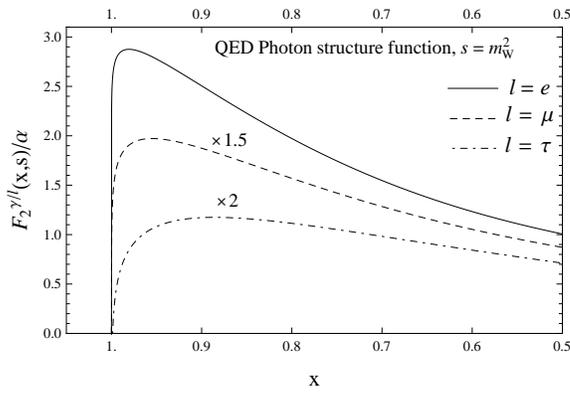
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Figure 3: QED structure functions of the photon divided by α for three charged leptons [40]. Note that the abscissa is flipped.

shapes of the cross sections from Fig 2. 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 functions of the photon $F_2^{\gamma/l}(x,s)$ in the cross sections σ_l [38]. Formally this is well seen by exploiting the parton model approach which tells us that σ_l can be written as

$$\sigma_l = \int \frac{dx}{x} F_2^{\gamma/l}(x,s)\sigma_{\nu l \to W}(xs), \tag{5}$$

where $\sigma_{\nu l \to W}(xs)$ are the cross sections of the subprocesses $\nu_l l^+ \to W^+$, the integration is performed over the kinematically allowed values of x. In the narrow width approximation $\sigma_{\nu l \to W}(xs)$ can be replaced by a Dirac δ function, so that $\sigma_{\nu l \to W}(xs) = 2\sqrt{2}\pi G_F \tau \delta(x-\tau)$. Substituting the latter into (5) yields

$$\sigma_l = 2\sqrt{2}\pi G_F F_2^{\gamma/l}(\tau,s). \tag{6}$$

Thus, one can conclude from (6) that our mechanism accounts for the similarity between σ_l and $F_2^{\gamma/l}(x,s)$: they turn out to be proportional to each other. Analytically, $F_2^{\gamma/l}(x,s)$ can be parameterized as [40]

$$F_2^{\gamma/l}(x,s) = \frac{\alpha}{2\pi}x\left[8x(1-x) - 1 + [x^2 + (1-x)^2]\log\left(\frac{s(1-x)}{m_l^2}\right)\right] \tag{7}$$

As an example, Fig. 4 shows the cross section for the reaction $\nu_e \gamma \to W^+ e^-$ given by (6) with (7) and that taken from [21]. The fact that the independently obtained structure function reproduces the straightforward Standard Electroweak Theory calculations within the error $< 20\%$ inspires to go into further details.

Let us utilize the cross sections for the subprocesses $\nu_l l^+ \to W^+$ in the Breit–Wigner form making the description of the resonances more physically realistic than the narrow width approximation. In this case, one has

$$\sigma_l = 24\pi\Gamma_{W \to \nu l}\Gamma \int_{x_{\min}}^{x_{\max}} \frac{dx}{x} \frac{F_2^{\gamma/l}(x,s)}{(xs - m_W^2)^2 + m_W^2\Gamma^2}, \tag{8}$$

where $\Gamma_{W \to \nu l}$ is the width of the decay $W^+ \to \nu_l l^+$, Γ is the total decay width of W^+. $x_{\min} = m_l^2/s$, $x_{\max} = (1 - m_l/\sqrt{s})^2$.

Substituting (7) into (8), we have performed calculations and display the results in comparison with the direct Standard Electroweak Theory predictions in Fig. 5. One can see that our
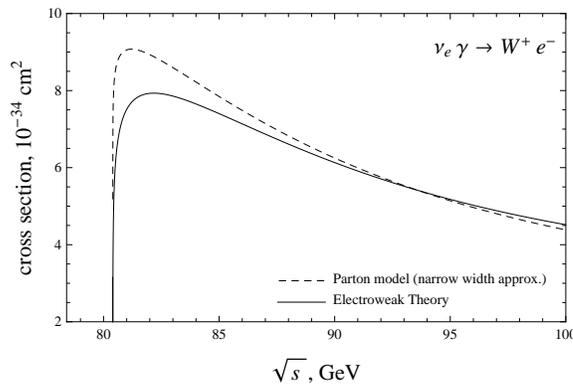
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Figure 4: Cross sections for $\nu_e\gamma \to W^+e^-$ as functions of the center-of-mass energy $\sqrt{s}$ straightforwardly calculated in the Standard Electroweak Theory (solid) [21] and found in the parton model with the narrow width approximation of the Glashow resonance (dashed).
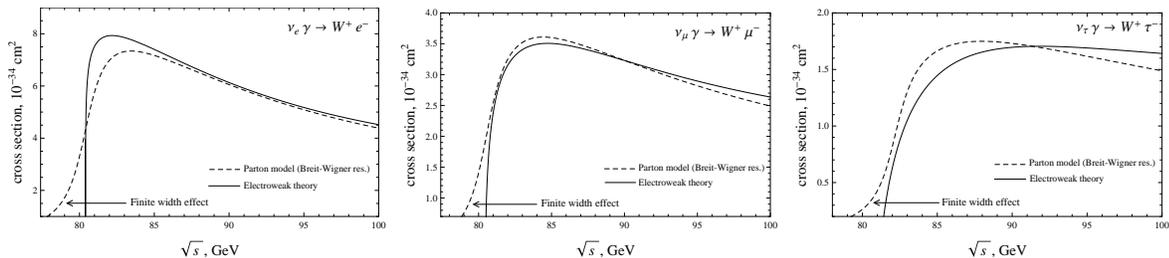

Figure 5: Cross sections for $\nu_l\gamma \to W^+l^-$, $l = e, \mu, \tau$, as functions of the center-of-mass energy $\sqrt{s}$ straightforwardly calculated in the Standard Electroweak Theory (solid) [21] and in the parton model with the Breit–Wigner form of the Glashow resonance (dashed).

model is again in a very good quantitative agreement with the straightforward standard calculations [21]. The shifts of the reaction thresholds to energies slightly lower than $\sqrt{s} = m_W + m_l$ are obviously due to the finite width effect [41]: the W propagator adopted in [21] has the structure $\sim 1/(q^2 - m_W^2)$, while we have used it in the general form $\sim 1/(q^2 - m_W^2 + im_W\Gamma)$. Everywhere in the calculations we have taken $\alpha = 1/128$, $G_F = 1.16 \times 10^{-5}$ GeV^{-2}, $m_e = 5 \times 10^{-4}$ GeV, $m_\mu = 0.105$ GeV, $m_\tau = 1.77$ GeV, $m_W = 80.4$ GeV, $\Gamma = 2.14$ GeV, $\Gamma_{\nu l} = 0.23$ GeV.

3 The Glashow resonance in neutrino–nucleus scattering

The Glashow resonances can be produced in neutrino–nucleus scattering $\nu_l N \to Nl^-W^+$. To find the corresponding cross sections one has to convolute (8) with the equivalent photon spectrum of the nucleus:

$$\sigma_{Nl} = \int_{y_0}^{1} dy\, f^{N/\gamma}(y)\sigma_l(ys), \tag{9}$$

where $y_0 = (m_W + m_l)^2/s$, $f^{N/\gamma}(y)$ is the equivalent photon spectrum. The general expression for $f^{N/\gamma}(y)$ can be written as [42]

$$f^{N/\gamma}(y) = \frac{\alpha Z^2}{2\pi}\frac{2 - 2y + y^2}{y}\int_{Q^2_{\min}}^{\infty} dQ^2 \frac{Q^2 - Q^2_{\min}}{Q^4}\left|F(Q^2)\right|^2, \tag{10}$$

where Q^2 is the momentum transfer to the nucleus, Z is the charge of the nucleus, $F(Q^2)$ is the electromagnetic nuclear formfactor normalized to $F(0) = 1$, $Q_{\min} = (yM_N)^2/(1 - y)$

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with M_N being the mass of the nucleus. The highest momentum components of the nuclear field establish the threshold for reactions $\nu_l N \to N l^- W^+$ in the laboratory reference frame. A detailed analysis shows that this threshold constitutes ~ 10 TeV [43] which is far below the point $E_\nu = 6.3$ PeV around which the Glashow resonance is usually expected to appear.

Let us consider the proton and nucleus of oxygen ^{16}O as the targets because UHE neutrinos can be detected in large volumes of water or ice as, for example, the IceCube kilometer-scale detector [24], the ANTARES undersea neutrino telescope [44] as well as the next generation deep-water neutrino telescopes KM3NeT [45] and NT1000 on Lake Baikal [46].

For example, the expected event rate distribution at IceCube reads

$$\frac{dN}{dE_\nu} = nt\Omega \sum_{l=e,\mu,\tau} \sigma_{Nl} \Phi_{\nu_l + \bar{\nu}_l}, \tag{11}$$

where n is the number of target nuclei in the effective volume of the detector, t is the time of exposure, Ω is the solid angle, $\Phi_{\nu + \bar{\nu}}$ is the flux of neutrinos and antineutrinos of flavor l. Taking the effective volume 0.44 km^3, $t = 365$ days, assuming the 1:1:1 neutrino flavor ratio (this is not inconsistent with the present IceCube data though there are arguments against the equal flavor composition [47]), neglecting the upward going electron and muon neutrinos (because they are very likely absorbed in the Earth), adopting $\Phi_{\nu + \bar{\nu}} = \Phi_0 (E_\nu / 1\text{GeV})^{-2.3}$, $\Phi_0 = 6.62 \times 10^{-7} / (\text{GeVcm}^2 \text{s sr})$ [48, 49], we have estimated the number of the Glashow resonance events per year produced through $\nu_l N \to N l^- W^+$ in the IceCube detector in the energy range from 15 TeV to 2 PeV:

$$N_{\mathrm{t}} = 1.1 \left(\frac{\Phi_0}{\dfrac{6.62 \times 10^{-7}}{\text{GeVcm}^2 \text{s sr}}} \right) \left(\frac{V}{0.44 \text{ km}^3} \right) \text{yr}^{-1}. \tag{12}$$

In the calculations of the cross sections σ_{Nl} we have taken into account three components of the equivalent photon spectrum relevant for this process: the elastic photon content of the proton [50], the inelastic photon content of the proton and neutron [51] and the photon distribution of nucleus ^{16}O given by (10) with the formfactor from [52].

It should be noted that the accuracy of the equivalent photon approximation in describing single W boson production in lepton–nucleon scattering is quite satisfactory [53] giving the error of the calculations less than 10% for the considered neutrino energies. Therefore, one can conclude that at least three events among the 37 TeV-PeV neutrino events already detected by the IceCube Collaboration in 988 days [34, 35] are due to the Glashow resonances excited by neutrinos interacting with the equivalent photons of the target, provided the neutrino flux behaves as assumed in (12).

4 Conclusions

We have analyzed the reactions $\nu_l \gamma \to W^+ l^-$, $(l = e, \mu, \tau)$ near the threshold $\sqrt{s} = m_W + m_l$. 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 these reactions proceed via the Glashow resonances. In more detail, the analysis indicates the following mechanism for these reactions: 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^-. It is essential that the leptons are radiated before the Glashow resonance appears. We call this mechanism "initial state charged lepton emission".

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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 the laboratory energies far below 6.3 PeV. For example, we have found that in the reactions $\nu_l {}^{16}\text{O} \to {}^{16}\text{O} W^+ l^-$, relevant for the IceCube experiment, the Glashow resonances can appear already at neutrino energies about a few tens of TeV.

It turns out that the Standard Model predicts a somewhat enhancement of the Glashow resonance event rate in ice in the energy region, where the IceCube Collaboration has detected 37 neutrino candidates with energies from ~ 30 TeV to 2 PeV [34, 35].

Our conclusions as well as numerical results 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 assumed to be CP-symmetric.

We would also like to note that there are processes described by diagrams whose structures at tree level coincide with that for $\nu_l \gamma \to W^+ l^-$. For example, one encounters such diagrams in single scalar and vector leptoquark production in lepton–gluon scattering $l(\nu_l) + \text{g} \to LQ + q$ [54, 55] which also lead to the cross sections with the feature resembling the radiation tail. Therefore, it is also fair to expect that they proceed, in analogy with the initial state lepton emission, via an initial state quark emission mechanism and the leptoquarks in these reactions are produced in s-channel subprocesses. Additionally, the W boson in the so-called decay of the UHE neutrino in a magnetic field $\nu_e \to W^+ e^-$ [56] probably appears through the resonant annihilation subprocess $\nu_e e^+ \to W^+$ as well.

Acknowledgements

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