PROCEEDINGS OF SCIENCE

The Glashow resonance in neutrino–nucleus scattering

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A hypothesis stating that reactions $\nu_l\gamma \to W^+l^-$ ($\bar{\nu}_l\gamma \to W^-l^+$), ($l = e, \mu, \tau$) near their thresholds $\sqrt{s} = m_W + m_l$ proceed through the s-channel subprocesses of resonance annihiltion of the neutrinos (antineutrinos) with the associated antileptons (leptons) into the W bosons (the so-called Glashow resonances) has been recently put forward. It has also been argued that if this hypothesis is true then the Glashow resonances can be produced in large volume neutrino detectors not only by the electron antineutrinos, as considered today in the literature, but also by muon and tau neutrinos and antineutrinos in scattering on the equivalent photons of atomic nuclei at laboratory neutrino energies far below 1 PeV (10^{15} eV). An analytical expression for the dependence of the cross sections of production of the Glashow resonances in coherent neutrino–nucleus collisions on the mass number and charge of the target nucleus valid for numerical estimations at $m_W^2/s \ll R_A M_A$ within the error of 20% is found (R_A and M_A are the radius and mass of the nucleus, respectively). Results are presented for the ^{16}O nucleus since this enters in the content of large volume water/ice neutrino detectors.

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1. Introduction

With the completion of the IceCube kilometer-scale neutrino detector located at the South Pole [1], the idea of observing cosmic ultra-high energy (UHE) electron antineutrinos through the resonant s-channel reaction $\bar{\nu}_e e^- \to W^-$ [2, 3] (the so-called Glashow resonance) is again in the focus of attention of physicists [4, 5, 6, 7, 8, 9, 10]. 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 [11, 12, 13] in terms of the Glashow resonance [14, 15]. 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.

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

$$\bar{\nu}_e e^- \to W^-, \tag{1.1}$$

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

$$\begin{aligned} \nu_e e^+ &\to W^+, \\ \nu_l l^+ &\to W^+, \\ \bar{\nu}_l l^- &\to W^-, \end{aligned} \tag{1.2}$$

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 (1.1) and ignoring (1.2) 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 [16]. Neutrinos may excite the Glashow resonances on such equivalent leptons generated by atomic nuclei [17], 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.

A hypothesis stating that reactions $\nu_l \gamma \to W^+ l^-$ ($\bar{\nu}_l \gamma \to W^- l^+$), ($l = e, \mu, \tau$) near their thresholds $\sqrt{s} = m_W + m_l$ proceed through the s-channel subprocesses of resonance annihilation of the neutrinos (antineutrinos) with the associated antileptons (leptons) into the W bosons (the Glashow resonances) has been recently put forward [18]. It has also been argued that if this hypothesis is true then the Glashow resonances can be produced in large volume neutrino detectors not only by the electron antineutrinos, as considered today in the literature, but also by muon and tau neutrinos and antineutrinos in scattering on the equivalent photons of atomic nuclei at the laboratory neutrino energies far below 1 PeV (10^{15} eV). In this paper, an analytical expression for the dependence of the cross sections of production of the Glashow resonances in coherent neutrino–nucleus collisions on

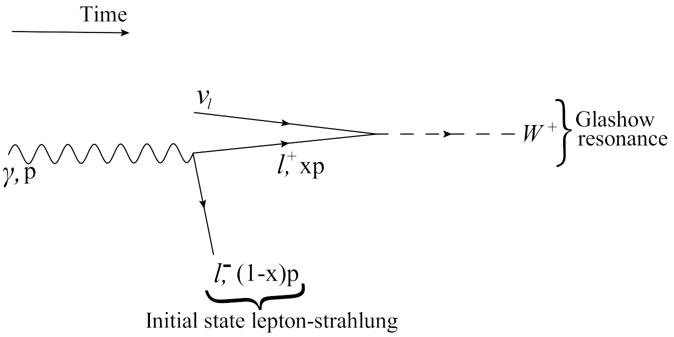

Figure 1: A schematic illustration of the initial state lepton emission mechanism for Glashow resonance production in $\nu_l\gamma \to W^+l^-$. The photon with a four-momentum p splits into a l^+l^- lepton pair before the Glashow resonance emerges (x is the fraction of the parent photon's momentum carried 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 $xs = m_W^2$ [18].

the mass number and charge of the target nucleus valid for numerical estimations at $m_W^2/s \ll R_A M_A$ within the error of 20% is found (R_A and M_A are the radius and mass of the nucleus, respectively). Results are presented for the ^{16}O nucleus.

2. Calculation of the cross sections

The Standard Model strongly suggests that the reactions $\nu_l\gamma \to W^+l^-$, $l = e, \mu, \tau$ proceed through the so-called initial state charged lepton emission schematically illustrated in Fig. 1 [18] (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 the neutrino-induced ones). According to this mechanism 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^-.

Therefore, if the mechanism is realized, the Glashow resonances can be produced by neutrinos of all the three flavors in coherent neutrino–nucleus collisions $\nu_l A \to A l^- W^+$ through interactions with the equivalent photons generated by the target nucleus. To find the corresponding cross sections one has to convolute the cross sections for $\nu_l\gamma \to W^+l^-$ with the equivalent photon spectrum of the nucleus:

$$\sigma_{Nl} = \int_{y_0}^{1} dy f^{N/\gamma}(y)\sigma_l(ys), \tag{2.1}$$

where $y_0 = 1/(M_A R_A)$ with M_A and R_A being the mass and radius of the nucleus, $f^{N/\gamma}(y)$ is the equivalent photon spectrum. In its turn, $\sigma_l(s)$ for each l can be also presented in the form a convolution of the cross section for the subprocess $\nu_l l^+ \to W^+$, $\sigma_{\nu l}(s)$, with the probability density to find l^+ in the photon, $f^{\gamma/l}(x)$,:

$$\sigma_l(s) = \int_{m_l^2/s}^{1} dx f^{\gamma/l}(x)\sigma_{\nu l}(xs). \tag{2.2}$$

The narrow width approximation for the Glashow resonances within which

$$\sigma_{\nu l}(xs) = 2\sqrt{2}\pi G_F \frac{m_W^2}{s}\delta\left(x - \frac{m_W^2}{s}\right)$$

greatly simplifies our calculations (G_F is the Fermi constant, $\delta(...)$ is the Dirac delta function). Let us also take [16]

$$f^{\gamma/l}(x) = \frac{\alpha}{2\pi}[x^2 + (1-x)^2]\log\left(\frac{m_W^2}{m_l^2}\right)$$

and [19]

$$f^{N/\gamma}(y) = \frac{2\alpha Z^2}{\pi x}\log\left(\frac{1}{xM_AR_A}\right)$$

(α is the fine structure constant, Z is the electric charge of the nucleus). Then, one finds that

$$\sigma_{Nl}(s) = \frac{2\sqrt{2}G_F\alpha^2 Z^2}{18\pi}\left[\frac{M_AR_Am_W^2}{s^3}(4M_A^2R_A^2m_W^4 - 9M_AR_Asm_w^2 + 18s^2) - 13 + 12\log\left(\frac{s}{M_AR_Am_W^2}\right)\right]\log\left(\frac{m_W^2}{m_l^2}\right). \tag{2.3}$$

One can see that (2.3) gives the sought-for cross sections as functions of the mass of the target nucleus and the mass number A (recall that $R_A \approx 7.25A^{1/3}$ GeV^{-1}). It should also be emphasized that (2.3) is valid when $m_W^2/s \ll M_AR_A$.

For example, let us consider how (2.3) works for the case of the electron neutrino and the nucleus of oxygen ^{16}O as the target because ultra high energy neutrinos can be detected in large volumes of water or ice (H_2O) as, for example, the IceCube kilometer-scale detector [1], the ANTARES undersea neutrino telescope [20] as well as the next generation deep-water neutrino telescopes KM3NeT [21] and NT1000 on Lake Baikal [22]. Figure 2 shows the result together with the cross section calculated with a realistic form factor of ^{16}O [18] (we call this the «exact» result). One can see the remarkable coincidence between (2.3) and the exact result. One can also notice in Fig. 3 that the formula (2.3) gives the cross sections within the error <20%. As the neutrino energy grows this error is reduced to values <10%. This is quite good for estimations. It should be noted that the obtained result is about two times lower than that presented in [23]. The cross sections for similar reactions induced by the other two flavors of neutrinos (μ and τ) can be found from (2.3) as well.

3. Conclusions

We have analyzed production of W bosons in coherent neutrino–nucleus scattering. As an example, we have considered the ^{16}O nucleus since this enters in the content of large volume water/ice neutrino detectors. The reactions $\nu_l{}^{16}\mathrm{O} \to {}^{16}\mathrm{O}W^+l^-$ are interesting in the light of the recent hypothesis stating that the Glashow resonances can be produced in interactions of neutrino

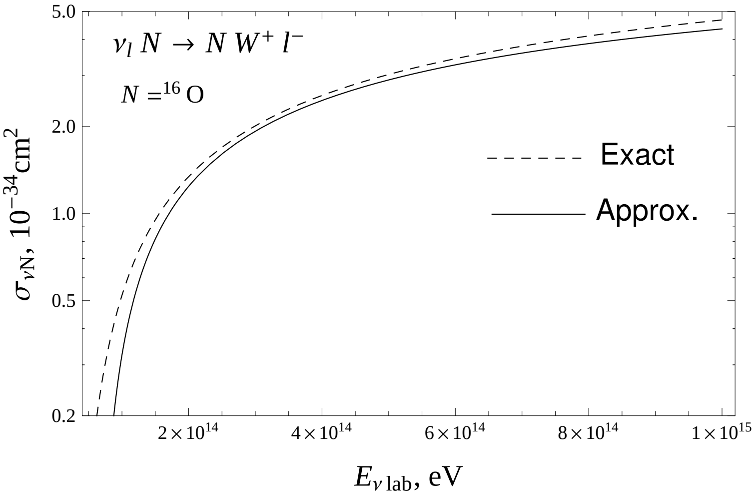

Figure 2: The cross sections for $\nu_e^{16}\text{O} \to^{16} \text{O}W^+e^-$ as functions of the incident neutrino energy in the laboratory reference frame. The solid curve represents the result given by (2.3), the dashed one is the exact result calculated in [18].

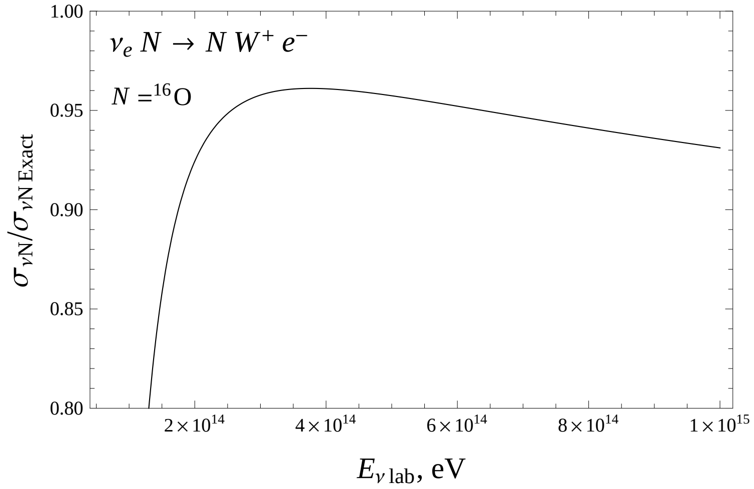

Figure 3: The ratio of the cross section for $\nu_e^{16}\text{O} \to^{16} \text{O}W^+e^-$ given by (2.3) and the exact one calculated in [18].

of all the three falvors ($l = e, \mu, \tau$) with the equivalent photons of charged particles [18]. According to this hypothesis, the Glashow resonances can appear already at neutrino energies of a few tens of TeV. An analytical expression for the dependence of the cross sections of production of the Glashow resonances in coherent neutrino–nucleus collisions on the mass number and charge of the target nucleus valid at $m_W^2/s \ll R_A M_A$ is found. It is shown that this expression is quite good for numerical estimations and coincides with the exact cross sections within the error of 20%. Our conclusions are exactly the same for the CP conjugate reactions $\bar{\nu}_l^{16}\text{O} \to^{16}\text{O}W^-l^+$ since the equivalent lepton spectrum of the photon is assumed to be CP-symmetric.

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