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On neutrino telescopes and their ability to infer astrophysical neutrino sources via the Glashow resonance

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Summary. — Using the Glashow resonance candidate event recently identified by IceCube, we infer the ultra-high energy astrophysical neutrino source. Since it can distinguish $\overline{\nu}_e$ from ν_e, the Glashow resonance is a valuable probe to identify the source of astrophysical neutrinos. With the available experimental information we set a constraint on the $\overline{\nu}_e$ fraction of astrophysical neutrinos and find that the μ-damped pγ source is excluded at about 2σ confidence level and that there is a weak preference for the pp source. Next generation neutrino telescopes will be able to distinguish between ideal pp and pγ sources with a high significance assuming a single power-law neutrino spectrum.

1. – Introduction

In 1960, and thus even before his contribution to electroweak theory [1], S. L. Glashow predicted the existence of a resonance for the process $\overline{\nu}_e + e^- \to \overline{\nu}_\mu + \mu^-$ for an intermediary boson being produced on-shell. Nowadays we know that such a resonance appears for a real intermediary W boson - the so-called Glashow resonance (GR) [2]. Since this resonance only appears for an incoming $\overline{\nu}_e$ but not for an incoming ν_e, it is a strong probe to distinguish antineutrinos from neutrinos. This can be used to infer information about astrophysical neutrino sources. In 2016, the IceCube observatory detected a GR candidate event at the energy $E_{\text{dep}} = 6.05 \pm 0.72$ PeV in the sample of partially contained events [3]. Here, we extract information on the ultra-high energy (UHE) neutrino source using this one event. In the future, we expect next generation experiments to detect more GR candidate events.

The discussion in these proceedings is based on ref. [4]. After discussing how the cross section of the GR is altered if we take Doppler broadening and initial state radiation (ISR) into account we examine the existing and future neutrino telescopes that can detect - among other events - the GR candidate events we are interested in. Next, we assess the neutrino sources we want to distinguish with the likelihood analysis that is carried out in the end.

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2. – The Glashow resonance and its cross section

At the leading level the GR cross section reads [3]

$$\sigma^{(0)}(s) = 24\pi\Gamma_W^2 \mathrm{Br}_{W^-\to\overline{\nu}_e e^-} \frac{s/M_W^2}{(s-M_W^2)^2+\Gamma_W^2 M_W^2}\,, \tag{1}$$

where $M_W \approx 80.433\,\mathrm{GeV}$ is the mass of the W boson, $\Gamma_W \approx 2.09$ GeV is the total decay width and $\mathrm{Br}_{W^-\to\overline{\nu}_e e^-} \approx 10.7\,\%$ is the branching ratio of the channel $W^- \to \overline{\nu}_e e^-$. As more and more UHE neutrino data is accumulated, a precise knowledge of the cross section becomes important. Hence we calculate two corrections to the leading-order cross section: the Doppler broadening and the ISR.
Due to the spread in the velocity of the target electrons the GR cross section is significantly broadened [2]. We calculate this effect following the method presented in ref. [5]. Please note that ref. [5] contains two typos which we corrected in the appendix of ref. [4]. The result is depicted in fig. 1 where we assume H_2O as the target. The peak is slightly reduced while the width of the cross section is broadened.

The ISR is included using the structure function approach. The modified cross section reads [6]

$$\sigma(E_\nu) = \int \mathrm{d}x\, \Gamma_{e/e}(x,Q^2)\sigma^{(0)}(x,Q^2,E_\nu)\,. \tag{2}$$

Here Q represents the energy scale, x is the longitudinal momentum fraction of the electron after the radiation of the photon, $\sigma^{(0)}$ is the cross section without the initial state photon and $\Gamma_{e/e}$ is the structure function of the electron. The structure function we use includes soft photons resummed to all orders and hard photons up to $\mathcal{O}(\alpha^3)$ [7]. The result is depicted in the turquoise dashed line of fig. 2. There are two main effects of the ISR. First of all, it reduces the peak at the resonance energy by almost 20%. Moreover, the so-called radiative return is visible above the resonance energy. The radiated

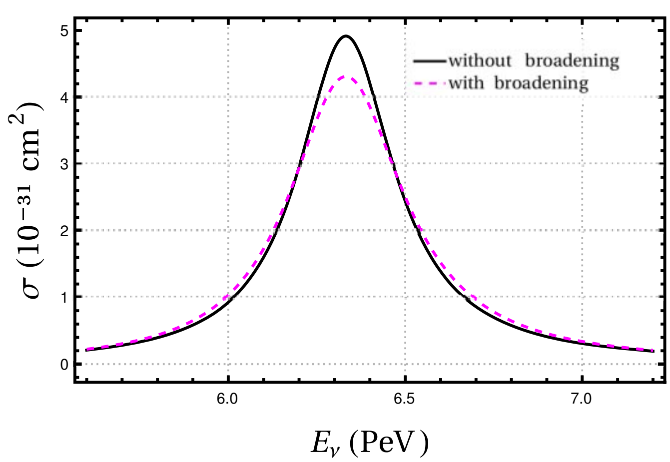

Fig. 1. – Cross section for the Glashow resonance process $\bar{\nu}_e + e^- \to W^- \to X$ both with (pink dashed) and without (black) Doppler broadening. Here, we assume ice (H_2O) as the target. The Doppler broadening effect reduces the peak while the width of the cross section is broadened.

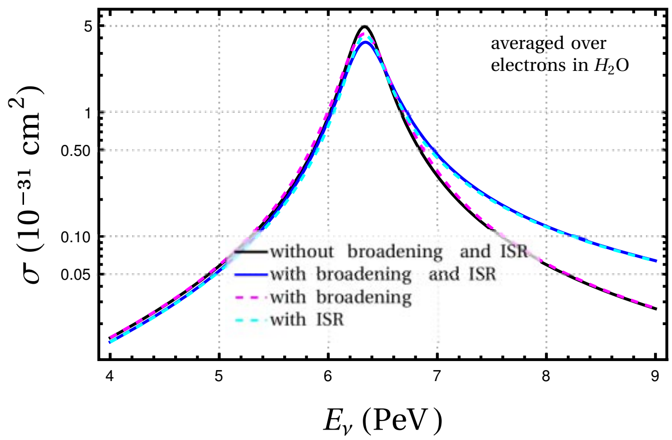

Fig. 2. – Cross section for the Glashow resonance process $\overline{\nu}_e + e^- \to W^- \to X$ with and without both initial state radiation and Doppler broadening. The black curve shows the cross section without both, the turquoise dashed one includes initial state radiation and the pink dashed one includes Doppler broadening. The blue curve is the cross section including both effects. The tabulated result of the curve including both effects is given in the supplemental material of [4]. Both the broadening and the so-called radiative return are visible. We averaged over the electrons in H_2O for the target.

photon carries away energy such that the intermediary W boson will be on-shell also for higher $\sqrt{s}$. This effect enhances the cross section above the resonance energy by more than a factor two. In fig. 2 the cross section is also shown for both effects combined (blue line). Both effects combined reduce the peak by about 30%.

3. – Experimental detection of the Glashow resonance

In this work we consider GR candidate events detected by neutrino telescopes. These usually consist of arrays of optical modules with photomultiplier tubes (PMTs) in water or ice. The first such project that was proposed was the Deep Underwater Muon and Neutrino Detector (DUMAND) project. Work began in 1976 [8]. DUMAND was supposed to be situated in the Pacific Ocean near Hawaii, consisting of an array of PMTs which should have been spread over a cubic kilometre. Even though DUMAND was never finished and the project has been terminated in 1995, it led to the development of many technical principles used in its successors [9]. At first, many Russian scientists participated in DUMAND. Due to the political situation the cooperation was ended in 1980. The Russian scientists then started their own project, the Baikal Deep Underwater Neutrino Telescope which was installed in Lake Baikal [9,10]. Since 2016, the cubic kilometre neutrino telescope Baikal-GVD is under construction in the southern part of Lake Baikal [11]. Later on, the Antarctic Muon And Neutrino Detector Array (AMANDA) was built in Antarctica. The latest version of AMANDA was made of 677 optical modules in 19 strings mostly at depths between 1500 and 2000 m. Until April 2009, AMANDA took data in its full configuration for nine years [9]. After AMANDA finished taking data it became part of IceCube, the well-known cubic kilometre neutrino observatory which is located in Antarctica as well. IceCube was the first neutrino telescope to detect a GR candidate event [3] which we discuss here. There are many future projects like IceCube-Gen2, Baikal-GVD, KM3NeT, P-ONE, TAMBO, TRIDENT [4] which will be sensitive to PeV neutrinos as well. Therefore we expect that more GR candidate events will be seen in the coming decades.

4. – Neutrino sources

Here, we aim to use the GR candidate event recently measured by IceCube to infer the UHE neutrino source. For these, a variety of source models exists [12-15]. Sources of the pp and pγ type can be distinguished. We consider three different neutrino sources. The first one is the pγ source. Cosmic rays collide with photons which produces charged pions (mostly π^+). These decay via $\pi^+ \to \mu^+\nu_\mu$ and $\mu^+ \to e^+\overline{\nu}_\mu\nu_e$ which leads to a neutrino to antineutrino ratio of 2:1. The pp source leads to nearly equal fractions of π^+ and π^- and hence to a neutrino to antineutrino ratio of 1:1. The last neutrino source that is considered in this work is the μ-damped pγ source. Here the muons significantly lose energy before decaying. Thus the neutrino to antineutrino ratio is 1:0. For our analysis we use the parameter

$$f_{\overline{\nu}_e} = \frac{\phi_{\overline{\nu}_e}}{\phi_{\overline{\nu}_e} + \phi_{\nu_e}} \,. \tag{3}$$

At Earth, we expect $f_{\overline{\nu}_e} = 0.23$ (pγ), 0.5 (pp) and 0 (μ-damped pγ). Please note that for the pγ source this only holds in the ideal case assuming that the neutrino production is dominated by the Δ-resonance. At very high energies multi-pion production becomes relevant which alters the expectation for $f_{\overline{\nu}_e}$. For a detailed discussion, please see ref. [4].

5. – Likelihood analysis and results

For the likelihood analysis we consider two different flux models. The first one is the unbroken single power-law model where the neutrino flux is modeled as

$$\frac{\mathrm{d}\Phi_{6\nu}}{\mathrm{d}E_\nu} = \Phi_0 \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma} 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\,, \tag{4}$$

where $\Phi_{6\nu}$ is the flux of all six neutrino species combined, Φ_0 is the overall normalization and γ is the spectral index [16]. However, the reachable energy of astrophysical accelerators always features a cutoff due to the Hillas criterion [17]. Therefore, we consider a second model which has an additional energy cutoff

$$\exp\left(-E_\nu/E_{\mathrm{cutoff}}\right) \,.$$

We use the framework of extended likelihood analysis of unbinned data [18] to calculate the likelihood for the parameter $f_{\overline{\nu}_e}$ using both the Bayesian and the frequentist approach. For details of the calculation please see ref. [4]. We find that the μ-damped pγ source ($f^{\oplus}_{\overline{\nu}_e} \approx 0$) is excluded by around 2σ level for all cases. Moreover, the current IceCube 4.6-year data weakly favor the pp source. However, we are not able to exclude the ideal pγ source considerably yet. We expect that future experiments like IceCube-Gen2 improve the sensitivity significantly. For example, if we assume that the true source is of the pp type ($f^{\oplus}_{\overline{\nu}_e} = 0.5$), we expect eleven GR events for the best-fit single power-law model within ten years of IceCube-Gen2. With an exponential cutoff at $E_{\mathrm{cutoff}} = 5\,\mathrm{PeV}$ the number of expected events goes down to three. For more details, see fig. 2 of ref. [4].

Note that in a later paper [19] a similar analysis was done (without including ISR and Doppler broadening) where projected sensitivities based on the combined exposure of planned Cherenkov neutrino telescopes are calculated and mixed production mechanisms are considered. The authors claim that pp and pγ sources can be distinguished with 2σ significance in the coming decades.

6. – Summary and outlook

In these proceedings, we discussed how the observation of GR candidate events can be used to distinguish different neutrino sources. For our analysis, we introduced secondary modifications of the leading cross section which will become more important once more GR candidate events are detected. Also, we discussed the experiments that can detect such events. The GR candidate event observed by IceCube so far can already rule out the μ-damped pγ source at 2σ level. Currently the pp source is weakly favoured.

In the future there are many promising projects. One example is IceCube-Gen2. Once these measure more GR candidate events, it will be reasonable to go beyond the single power-law flux model. In the case of vastly increased statistics, the GR could also be used to produce a map of the sky and identify associated PeVatrons.

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