Glashow resonance as a window into cosmic neutrino sources

V. Barger,\textsuperscript{1} Lingjun Fu,\textsuperscript{2} J.G. Learned,\textsuperscript{3} D. Marfatia,\textsuperscript{3} S. Pakvasa,\textsuperscript{3} and T.J. Weiler\textsuperscript{2}

\textsuperscript{1}Department of Physics, University of Wisconsin, Madison, WI 53706, USA
\textsuperscript{2}Department of Physics & Astronomy, Vanderbilt University, Nashville, TN 37235, USA
\textsuperscript{3}Department of Physics & Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA

Abstract

The Glashow resonance at $E_{\nu} = 6.3$ PeV is a measure of the $\bar{\nu}_e$ content of the astrophysical neutrino flux. The fractional $\bar{\nu}_e$ content depends on the neutrino production model at the cosmic neutrino source, and the environment at the source. Thus, the strength of the Glashow resonance event rate is a potential window into astrophysical sources. We quantify the “Glashow resonometer” and comment on the significance that no Glashow events are observed in the IceCube three–year data.
I. INTRODUCTION

The rate of interaction of $\nu_e$, $\nu_\mu$, $\nu_\tau$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$, with electrons is mostly negligible compared to interactions with nucleons. However, the case of $\bar{\nu}_e$ is unique because of resonant scattering, $\bar{\nu}_e e^- \rightarrow W^- \rightarrow$ anything, at $E_\nu \approx 6.3$ PeV. The $W^-$ resonance in this process is commonly referred to as the Glashow resonance [1]. The signal for $\bar{\nu}_e$ at the Glashow resonance, when normalized to the total $\nu + \bar{\nu}$ flux, can be used to differentiate among the main primary mechanisms for neutrino-producing interactions in optically thin sources of cosmic rays [2].

In 2012, IceCube released the first two-year equivalent dataset, observing high-energy non-atmospheric neutrino events for the first time [3, 4]. The maximum neutrino energy inferred was 1–2 PeV. In 2014, IceCube reported its three-year dataset [5]. The maximum neutrino energy inferred to date remains at $\sim 2$ PeV. The energy resolution on the observed events is $\sim 25\%$. In particular, Glashow resonance events should produce showers that are not (yet) observed. The integrated cross section of the resonance is comparable for some flavor models to that of the non-resonant spectrum integrated above a PeV, which implies that the falling power law ($E_\nu^{-\alpha}$) of the incident neutrino spectrum is effectively canceled and that resonant events could have been seen [6].

In this Letter, we evaluate the ratio of the expected number of Glashow events at 6.3 PeV to the number of non-resonant events expected above various minimum energies ($\sim$ PeV) for six popular cosmic neutrino source models.

II. SIX ASTROPHYSICAL NEUTRINO SOURCE MODELS

We consider six possible source models:

(i) $pp \rightarrow \pi^\pm$ pairs $\rightarrow \nu_e + \bar{\nu}_e + 2\nu_\mu + 2\bar{\nu}_\mu$, referred to as the “$\pi^\pm$ mode”;
(ii) $pp \rightarrow \pi^\pm$ pairs $\rightarrow \nu_\mu, \bar{\nu}_\mu$ only, referred to as the “damped $\mu^\pm$ mode”;
(iii) $p\gamma \rightarrow \pi^+$ only, $\rightarrow \nu_e + \nu_\mu + \bar{\nu}_\mu$, referred to as the “$\pi^+$ mode”;
(iv) $p\gamma \rightarrow \pi^+$ only, referred to as the “damped $\mu^+$ mode”;
(v) charm production and immediate decay to $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$, referred to as the “prompt” mode; and
(vi) $\beta$-decay of cosmic neutrons to $\bar{\nu}_e$, referred to as the “neutron decay (or $\beta$ decay) mode”.

The initial flavor content of the produced neutrinos in these six models are summarized in the second column of Table I.

When the $\pi^\pm$ mode occurs in an astrophysical source, isospin invariance yields a roughly equal ratio of $\pi^+$, $\pi^-$, and $\pi^0$ production, followed by decay of the charged $\pi^\pm$s through the $\mu^\pm$ chain to produce equal numbers of $\nu_\mu$ and $\bar{\nu}_\mu$, a number of $\nu_e$ plus $\bar{\nu}_e$, equal to a half of $\nu_\mu$ plus $\bar{\nu}_\mu$, and roughly equal numbers of $\nu_e$ and $\bar{\nu}_e$. The rest-frame lifetimes of the charged pions and muons are $2.6 \times 10^{-8}$ s and $2.2 \times 10^{-6}$ s, respectively. Since the rest-frame lifetime of the muon exceeds that of the charged pion by a factor of 85, it is possible for $\pi^\pm$ decay to take place but the subsequent $\mu^\pm$ decay to be inhibited [7]. This would happen if the muon in the decay chain loses energy in the source environment before it decays (e.g., by synchrotron radiation in a $\vec{B}$-field, or by scattering). In a falling spectrum, the decay of a lower-energy muon would make a negligible contribution. This damped $\mu^\pm$ mode results in only $\nu_\mu$ and $\bar{\nu}_\mu$ being produced at the source; flavor mixing between the source and Earth then produces a small amount of $\bar{\nu}_e$.

In contrast to charged-pion production by $pp$ scattering, charged pions may be produced by $p\gamma$ scattering. Here, the $\Delta^+$ resonance contributes to produce $\pi^+ + n$ and $\pi^0 + p$, in
TABLE I: Neutrino flavor ratios at source, component of $\bar{\nu}_e$ in total neutrino flux at Earth after mixing and decohering, and consequent relative strength of Glashow resonance, for six astrophysical models. (Neutrinos and antineutrinos are shown separately, when they differ.)

| Source flavor ratio | Earthly flavor ratio | $\bar{\nu}_e$ fraction in flux ($\mathcal{R}$) |
|---------------------|----------------------|----------------------------------------------|
| $pp \rightarrow \pi^\pm$ pairs | (1:2:0) | (1:1) | 18/108 = 0.17 |
| $w/$ damped $\mu^\pm$ | (0:1:0) | (4:7:7) | 12/108 = 0.11 |
| $p\gamma \rightarrow \pi^+$ only | (1:1:0) | (14:11:11) | (4:7:7) | 8/108 = 0.074 |
| $w/$ damped $\mu^+$ | (0:1:0) | (0:0:0) | (4:7:7) | (0:0:0) | 0 |
| charm decay | (1:1:0) | (14:11:11) | 21/108 = 0.19 |
| neutron decay | (0:0:0) | (1:0:0) | (0:0:0) | (5:2:2) | 60/108 = 0.56 |

the ratio of $1 : 2$. Since $\pi^-$ production is suppressed and the $\pi^+$ mode produces no $\bar{\nu}_e$s at the source, only a small amount of $\bar{\nu}_e$ arises from mixing [8]. If, in addition, the $\mu^+$s in $p\gamma$ mode are damped, then no antineutrinos are produced at all at the source, and so even with mixing there will be no $\bar{\nu}_e$s at Earth.

Charmed particles decay promptly (e.g. the $D^\pm$ has a lifetime of $1.0 \times 10^{12}$ s) and semileptonically to $e^\pm$ or $\mu^\pm$ (e.g., the $D^\pm$ has a 34% branching ratio to these modes). Lepton universality ensures that equal numbers (modulo small mass differences) of $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, and $\bar{\nu}_\mu$ are produced, while production of $\nu_\tau$ and $\bar{\nu}_\tau$ is kinematically suppressed. Thus, $\bar{\nu}_e$s produced in charm decay will arrive at Earth.

Finally, there may be sources that inject a nearly pure neutron flux [9]. Such would be the case if Fe is emitted and subsequently dissociated to protons and neutrons, with the charged protons then degraded in energy, or swept aside, by a magnetic field at the source. Such would also be the case if the cosmic accelerator entrains and accelerates charged protons, with cosmic-ray escape occurring via $p_{\text{entrained}} \rightarrow n + \pi^+$. This escaping (and pointing) beta beam decays to pure $\bar{\nu}_e$, leading to a large amount of $\bar{\nu}_e$ arriving at Earth, even after mixing.

Each of these six models are possible, as are combinations of the six. For our purposes, we consider each model in isolation, and show how the rate for Glashow resonant events can serve as a barometer ("resonometer") distinguishing among these six source models.
A caveat is in order here. It has been shown, especially in Ref. [10], that multi-pion contributions can produce antineutrinos which via mixing ensure some \( \bar{\nu}_e \)s at Earth. These multi-pion contributions are not included in our discussion here. For certain source parameters, the “contamination” from multi-pion processes can be large. In addition, we assume that possible damping of muons at the sources is complete; it may be incomplete, in which case results will be intermediate between the cases considered here. We mention in passing that the effect of kaon decays on source neutrino flavor ratios is small in the energy range of interest [10]. All in all, our results must be treated as suggestive. If and when Glashow resonance events are observed, a more careful treatment than presented here will be warranted. Until Glashow resonance events are observed, our results can be considered motivational.

At this early stage of astrophysical data collection, it is a good approximation [11] to assume that tribimaximal mixing [12] holds. Then, the evolution \( \nu_\alpha \rightarrow \nu_\beta \), with \( \alpha \) and \( \beta \) any elements of the three-flavor set \( \{ e, \mu, \tau \} \), is described in terms of the PMNS matrix \( U \), by the symmetric propagation matrix \( P \) whose positive definite elements are

\[
P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}.
\]

III. RESONANT AND NON-RESONANT EVENTS

The resonant cross section for \( \bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{hadrons} \) is

\[
\sigma_{\text{Res}}(s) = 24\pi \frac{\Gamma_W^2}{M_W^2} B(W^- \rightarrow \bar{\nu}_e e^-) B(W^- \rightarrow \text{had}) \frac{(s/M_W^2)}{(s - M_W^2)^2 + (M_W \Gamma_W)^2},
\]

where \( M_W \) is the \( W \) mass (80.4 GeV), \( \Gamma_W \) is the \( W \)’s FWHM (2.1 GeV), and \( B(W^- \rightarrow \bar{\nu}_e e^-) \) and \( B(W^- \rightarrow \text{had}) \) are \( W^- \) branching ratios to the \( \bar{\nu}_e e^- \) state (11%) and the hadronic state (67%), respectively. At the peak,

\[
\sigma_{\text{Res}}^{\text{peak}}(s) = \frac{24\pi B(W^- \rightarrow \bar{\nu}_e e^-) B(W^- \rightarrow \text{had})}{M_W^2} = 3.4 \times 10^{-31} \text{cm}^2.
\]

Consequently, the resonant cross section may be written as

\[
\sigma_{\text{Res}}(s) = \left[ \frac{\Gamma_W^2}{(s - M_W^2)^2 + (M_W \Gamma_W)^2} \right] \sigma_{\text{Res}}^{\text{peak}}(s).
\]

The \( W \)’s width is small compared to the \( W \)’s mass \( (\frac{\Gamma_W}{M_W} = 2.6\%) \), and the experimental resolution will always exceed by far the \( W \) width. Thus, we are justified in using the “narrow width approximation” (NWA) throughout. A contour integration in \( s \) over the \( s \)-dependent bracketed expression in Eq. (4), and the residue theorem, yields the value \( \pi M_W \Gamma_W \). Thus, the resulting NWA is simply

\[
\sigma(s)_{\text{Res}} = (\pi M_W \Gamma_W) \sigma_{\text{Res}}^{\text{peak}}(s) \delta(s - M_W^2),
\]

\[4\]
and the number of resonant events per unit time and unit steradian is

\[
\left( \frac{N}{T\Omega} \right)_{\text{Res}} = N_e (\pi M_W \Gamma_W) \sigma_{\text{Res}}^{\text{peak}} \int dE_{\bar{\nu}e} \left( \frac{dF_{\bar{\nu}e}}{dE_{\bar{\nu}e}} \right) \delta(s - M_W^2)
\]

\[
= \frac{N_p}{2m_e} (\pi M_W \Gamma_W) \sigma_{\text{Res}}^{\text{peak}} \left( \frac{dF_{\bar{\nu}e}}{dE_{\bar{\nu}e}} \right) \bigg|_{E_{\bar{\nu}e} = 6.3 \text{ PeV}},
\]

where \(N_e = N_p\) is the number of electrons or protons in the detector volume.

In contrast, the integrated continuum (non-resonant) neutrino event rate above \(E_{\nu}^{\text{min}} \sim \text{PeV}\) is given by

\[
\left( \frac{N}{T\Omega} \right)_{\text{non-Res}} = N_{n+p} \int_{E_{\nu}^{\text{min}}}^{E_{\nu}^0} dE_{\nu} \left( \frac{dF_{\nu}}{dE_{\nu}} \right) \sigma(E_{\nu}) \nu N \approx N_{n+p} \left( \frac{\sigma_{\nu N}^{\text{CC}}(E_{\nu})}{(\alpha - 1.40)} \frac{dF_{\nu}}{dE_{\nu}} \right) \bigg|_{E_{\nu} = 6.3 \text{ PeV}},
\]

where \(N_{n+p}\) is the number of nucleons in the detector volume, and \(\frac{dF_{\nu}}{dE_{\nu}}\) is the total (summed over flavors) \(\nu\) plus \(\bar{\nu}\) flux. Here we have assumed an \(E^{0.40}\) energy dependence for \(\sigma_{\nu N}\) as predicted for the 1–6 PeV region in Ref. [13], and we have included only the charged-current cross section since the neutral-current contribution appears with lower visible energy; see Fig. [1]. The simple Fermi shock-acceleration mechanism yields \(\alpha = 2.0\), whereas an earlier statistical study of the first-release dataset concluded that \(\alpha\) was constrained by the absence of Glashow events in the IceCube data to \(\alpha \geq 2.3\) [14] [15].

From Eqs. [6] and [7], we find the ratio of resonant Glashow events to non-resonant continuum events to be

\[
\frac{N_{\text{Res}}}{N_{\text{non-Res}}(E_{\nu} > E_{\nu}^{\text{min}})} = \frac{\pi}{2} \left( \frac{\Gamma_W}{M_W} \right) \left( \frac{\sigma_{\nu N}^{\text{CC}}}{\sigma_{\nu N}^{\text{CC}}(E_{\nu} = 6.3 \text{ PeV})} \right) (\alpha - 1.40) \left( \frac{E_{\nu}^{\text{min}}}{6.3 \text{ PeV}} \right)^{\alpha - 1.40} \mathcal{R},
\]

\[
= 9.8 \times (\alpha - 1.40) \left( \frac{E_{\nu}^{\text{min}}}{6.3 \text{ PeV}} \right)^{\alpha - 1.40} \mathcal{R}, \quad \text{with} \quad \mathcal{R} \equiv \left[ \frac{dF_{\bar{\nu}e}}{dE_{\bar{\nu}e}} \bigg|_{E_{\bar{\nu}e} = 6.3 \text{ PeV}} \right] \frac{dF_{\nu}}{dE_{\nu}}.
\]

Here we have taken \(N_p = N_n\) in the detector material, and set \(\sigma_{\nu N}^{\text{CC}} = \sigma_{\nu e N}^{\text{CC}} = 1.42 \times 10^{-33} \text{ cm}^2\) at \(E_{\nu} = 6.3 \text{ PeV}\) [13]. \(\mathcal{R}\) is the ratio of the \(\bar{\nu}_e\) flux that produces the resonance events to the total \(\nu\) flux that produces the continuum events; \(\mathcal{R}\) is model-dependent number, exhibited for each of our six models in the final column of Table [1]. We stress that the ratio in Eq. [8] is valid for down-coming events, but not for up-coming events. The reason is that the large resonant cross section at 6.3 PeV implies that 6.3 PeV neutrinos are strongly absorbed if transiting the Earth, thereby eliminating the possibility for up-coming Glashow events [13].

In Table [1], we list the ratio of Glashow events to continuum events above \(E_{\nu}^{\text{min}} = 1, 2, 3, 4, 5 \text{ PeV}\), with \(\alpha = 2.0\) (2.3), for the six models of cosmic neutrino production under consideration. Note that we keep the value of \(E_{\nu}^{\text{min}}\) well below the energy region of the resonance: at the energy value of the peak minus one FWHM, the incident neutrino
FIG. 1: Cross sections for the resonant process, $\bar{\nu}_e + e^- \to W^- \to$ hadrons, and the non-resonant process, $\nu_e + N \to e^- +$ hadrons, in the 1–10 PeV region.

energy is $6.3 \text{ PeV} \left(1 - \Gamma_W/M_W\right)^2 \approx 6.3 \text{ PeV} \left(1 - 0.052\right) = 6.0 \text{ PeV}$. The numbers of expected resonant events is greatly reduced from the ratio of resonant to non-resonant cross sections by the additional factors. The cross section ratio at 6.3 PeV is 240: see Fig. 1. The ratio is $1/38$. The $\alpha$-dependent factor $\left[(\alpha - 1.40) \left(\frac{1 \text{ PeV}}{6.3 \text{ PeV}}\right)^{\alpha-1.40}\right]$ yields about 0.2 for both $\alpha$’s of interest, 2.0 and 2.3. The end result is about $2R$ for the ratio of resonant events to non-resonant events above 1 PeV. More precise numbers are listed in the table.

Since three down-going shower events have been observed at IceCube in the 1-2 PeV region, the expected number of Glashow events is found by multiplying the first numerical column of Table II by three. These expected resonant event numbers are 1.0 (0.9), 0.7 (0.5), 0.4 (0.4), 0 (0), 1.1 (1.0), and 3.3 (2.8), for the six models, and for $\alpha = 2.0 (2.3)$, respectively. Since no 6.3 PeV events are observed, all models remain viable except perhaps the final one, where neutron decay to pure $\bar{\nu}_e$ predicts some resonance events at Earth. In terms of Poisson statistics, when $\langle N \rangle$ events are expected, the probability that none are observed is $P(0|\langle N \rangle) = e^{-\langle N \rangle}$; thus, the six models yield Poissonian occurrence probabilities of 37%, 50%, 67%, 100%, 33%, and 4% for $\alpha = 2$, and slightly larger probabilities for $\alpha = 2.3$.

For the sake of completeness, we briefly consider the possibility of exotic neutrino properties that modify the flavor mix of neutrinos, specifically neutrino decay and pseudo-Dirac neutrino oscillations.

Neutrino decay [16] allows the flavor mix to deviate significantly from the democratic mix. Observation of a significant $\bar{\nu}_e$ flux from SN1987A precludes any observable effects of $\nu_1$ decay on $L/E$ scales of astrophysical interest. In the case of a normal hierarchy (with
TABLE II: Ratio of resonant event rate around the 6.3 PeV peak to non-resonant event rate above $E_{\nu}^{\text{min}} = 1, 2, 3, 4, 5$ PeV. The single power-law spectral index $\alpha$ is taken to be 2.0 and 2.3 for the non-parenthetic and parenthetic values, respectively. As an example, the single power-law extrapolation from the three events observed just above 1 PeV predicts a mean number of observed resonance events around 6.3 PeV equal to the first numerical column times 3.

| $E_{\nu}^{\text{min}}$ (PeV) | 1     | 2     | 3     | 4     | 5     |
|-----------------------------|-------|-------|-------|-------|-------|
| $pp \rightarrow \pi^{\pm}$ pairs | 0.33 (0.29) | 0.50 (0.53) | 0.64 (0.77) | 0.76 (1.0) | 0.87 (1.2) |
| damped $\mu^{\pm}$         | 0.22 (0.18) | 0.33 (0.34) | 0.42 (0.50) | 0.49 (0.64) | 0.56 (0.79) |
| $p\gamma \rightarrow \pi^{+}$ only | 0.14 (0.12) | 0.22 (0.23) | 0.28 (0.33) | 0.33 (0.43) | 0.38 (0.53) |
| damped $\mu^{+}$           | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| charm decay                 | 0.37 (0.32) | 0.56 (0.60) | 0.72 (0.86) | 0.85 (1.1) | 0.98 (1.4) |
| neutron decay               | 1.1 (0.94) | 1.7 (1.8) | 2.1 (2.5) | 2.5 (3.3) | 2.9 (4.0) |

mass ordering $m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$), the $\nu_2$ and $\nu_3$ mass eigenstates may decay completely to $\nu_1$, whose flavor content ratios are $|U_{e1}|^2 : |U_{\mu1}|^2 : |U_{\tau1}|^2 = 4 : 1 : 1$ for both $\nu$ and $\bar{\nu}$. The $\nu_e$ content of the neutrino flux at Earth is then 1/3 which may be an enhancement. On the other hand, if the mass hierarchy is inverted (with $m_{\nu_3} < m_{\nu_1} < m_{\nu_2}$), then both $\nu_1$ and $\nu_3$ are stable and a variety of final flavor ratios are possible, depending on the intial ratios of $\nu_1$, $\nu_2$, and $\nu_3$, and the decay mode of $\nu_2$.

Another possibility for deviations from standard flavor mixes [17] arises in scenarios of pseudo-Dirac neutrinos [18], in which each of the three neutrino mass eigenstates is a doublet with tiny mass differences less than $10^{-6}$ eV (to evade detection so far). The smallness of the mass difference tells us that the mixing angle between the active state with $SU(2)$ couplings, and the sterile state without, is necessarily maximal. For cosmically-large $L/E$, the flux of each active flavor is therefore reduced by a half. Of course, if all three flavors are reduced by a half, there is no change in the flavor ratios; however, at intermediate energies each flavor

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1 In fact, observing an energy-dependence of flavor mixes of high energy cosmic neutrinos is the only known way to detect mass-squared differences in the range $10^{-18} - 10^{-12}$ eV$^2$. 
can be reduced or not, leading to a possible suppression of the absolute flavor ratio for \( \bar{\nu}_e \) by \( R_{\bar{\nu}_e}^{D} / R_{\bar{\nu}_e} \) of roughly 1/2, or an enhancement of the \( \bar{\nu}_e \) flux ratio of roughly 2. (Note that the maximal suppression/enhancement will be a bit less than 1/2 or 2 if there is a \( \nu_e \) flux present.)

IV. CONCLUSIONS

Normalized to the three down-coming IceCube events in the 1-2 PeV range, we find that the number of predicted resonant Glashow events ranges from zero (for the damped \( \mu^+ \) mode, which generates no antineutrinos) to over three (for the neutron decay mode which generates only antineutrinos). The other four popular neutrino-generating modes give intermediate values. Thus we have demonstrated that the fraction of resonance events is a potential discriminator among the popular neutrino-generating astrophysical models.

Our calculations are done in a somewhat idealized approximation. For example, in pion production from \( p\gamma \) collisions, we consider only the contribution of the \( \Delta^+ \) intermediate states. Also, we do not consider the possibility that more than one neutrino source model may be contributing. When more data become available, refinements on our “Resonometer” will become necessary.

Until that day, we conclude that the absence of Glashow resonance events in IceCube favors the lower values of the fractional \( \bar{\nu}_e \) flux. Should this non-observation of resonance events continue, the “damped \( \mu^+ \) mode” \( p\gamma \rightarrow \pi^+n \rightarrow n + \mu^+ + \nu_\mu \) would become uniquely favored. Caveats to this conclusion include the possibility of pseudo-Dirac neutrino oscillations, and the possibility of neutrino decay.

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