UHE NEUTRINOS AND THE GLASHOW RESONANCE

Raj Gandhi
Harish Chandra Research Institute
Allahabad

(Work in progress with Atri Bhattacharya, Werner Rodejohann and Atsushi Watanabe)

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The Glashow Resonance (GR) refers to the Standard Model process which results in the resonant formation of an intermediate $W^-$ in $\bar{\nu}_e e$ at $E_{\text{nu}} = 6.3$ PeV.

_Glashow '60, Berezinsky and Gazizov, '77_

- The final states could be to leptons or hadrons, giving both showers and muon or tau lepton tracks in UHE detectors.

- While usually dwarfed by the neutrino-nucleon cross-section, the anti-neutrino-electron cross-section at the GR is higher than the neutrino-nucleon cross-section at all energies upto $10^{21}$ eV.
The Glashow Resonance....why it could be important

The region where an extra-galactic UHE flux emerges above the atmospheric background but stays below current IC bounds is in the neighbourhood of the GR
Due to these reasons, it could be useful to look carefully at this small but important region.

Additionally, it could be useful to identify events with unique signatures and low backgrounds in its neighbourhood.

Could it be used as a tool to see X-galactic diffuse neutrino signals?
GR Xsecs.....

\[
\frac{d\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu)}{dy} = \frac{G_F^2 m E_\nu}{2\pi} \frac{4(1 - y)^2[1 - (\mu^2 - m^2)/2m E_\nu]^2}{(1 - 2m E_\nu/M_W^2)^2 + \Gamma_W^2/M_W^2}
\]

\[
\frac{d\sigma(\bar{\nu}_e e \rightarrow \text{hadrons})}{dy} = \frac{d\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu)}{dy} \cdot \frac{\Gamma(W \rightarrow \text{hadrons})}{\Gamma(W \rightarrow \mu \bar{\nu}_\mu)}
\]

Lab frame, m= electron mass, y= E_mu/E_nu
The cross-sections

\[ \bar{\nu}_e e \rightarrow \text{hadrons} , \ \bar{\nu}_e e \rightarrow \bar{\nu}_e e , \ \bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu , \ \bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau \]

are resonant
The Glashow Resonance......Relevant Cross-sections

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma$ [cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu e \rightarrow \nu_\mu e$</td>
<td>$5.86 \times 10^{-36}$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu e \rightarrow \bar{\nu}</em>\mu e$</td>
<td>$5.16 \times 10^{-36}$</td>
</tr>
<tr>
<td>$\nu_\mu e \rightarrow \mu \nu_e$</td>
<td>$5.42 \times 10^{-35}$</td>
</tr>
<tr>
<td>$\nu_e e \rightarrow \nu_e e$</td>
<td>$3.10 \times 10^{-35}$</td>
</tr>
<tr>
<td>$\bar{\nu}_e e \rightarrow \bar{\nu}_e e$</td>
<td>$5.38 \times 10^{-32}$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>e e \rightarrow \bar{\nu}</em>\mu \mu$</td>
<td>$5.38 \times 10^{-32}$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>e e \rightarrow \bar{\nu}</em>\tau \tau$</td>
<td>$5.38 \times 10^{-32}$</td>
</tr>
<tr>
<td>$\bar{\nu}_e e \rightarrow \text{hadrons}$</td>
<td>$3.41 \times 10^{-31}$</td>
</tr>
<tr>
<td>$\bar{\nu}_e e \rightarrow \text{anything}$</td>
<td>$5.02 \times 10^{-31}$</td>
</tr>
<tr>
<td>$\nu_\mu N \rightarrow \mu^- + \text{anything}$</td>
<td>$1.43 \times 10^{-33}$</td>
</tr>
<tr>
<td>$\nu_\mu N \rightarrow \nu_\mu + \text{anything}$</td>
<td>$6.04 \times 10^{-34}$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu N \rightarrow \mu^+ + \text{anything}$</td>
<td>$1.41 \times 10^{-33}$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu N \rightarrow \bar{\nu}</em>\mu + \text{anything}$</td>
<td>$5.98 \times 10^{-34}$</td>
</tr>
</tbody>
</table>

RG, Quigg, Reno and Sarcevic ‘95
We note that, at the GR........

\[
\frac{\bar{\nu}_e e \rightarrow \text{anything}}{\nu_\mu + N \rightarrow \mu + \text{anything}} \approx 360
\]

\[
\frac{\bar{\nu}_e e \rightarrow \text{hadrons}}{\nu_\mu + N \rightarrow \mu + \text{anything}} \approx 240
\]

\[
\frac{\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu}{\nu_\mu + N \rightarrow \mu + \text{anything}} \approx 40
\]

\[
\frac{\bar{\nu}_e + e \rightarrow \bar{\nu}_\mu + \mu}{\nu_\mu + e \rightarrow \mu + \nu_e} \approx 1000
\]

standard CC process total

pure muon track, unique if contained initial vertex

pure tau track, unique if contained lollipop

background to pure muon with contained initial vertex
Detecting the GR

- Earlier studies have focused on its detection via shower events and on how the GR can be used as a discriminator of the relative abundance of pp vs p-gamma sources.

Learned and Pakvasa ‘95, Anchordoqui, Goldberg, Halzen and Weiler ‘05, Bhattacharjee and Gupta ‘05, Maltoni and Winter ‘08, Hummer, Maltoni, Winter and Yaguna ‘10, Xing and Zhou ‘11

We study here its potential as a discovery channel for UHE neutrinos, using both showers and lepton tracks.
The Generalized UHE Neutrino Flux.............

Parametrize the flux at source as

\[ \Phi_{\text{source}} = x \Phi_{\text{source}}^{pp} + (1 - x) \Phi_{\text{source}}^{p\gamma}. \]

- **Standard oscillations with tribimaximal mixing give**

\[ \Phi_{\text{earth}}^{pp} \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} + \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \]

\[ \Phi_{\text{earth}}^{p\gamma} \propto \begin{pmatrix} 0.78 \\ 0.61 \\ 0.61 \end{pmatrix} + \begin{pmatrix} 0.22 \\ 0.39 \\ 0.39 \end{pmatrix}. \]
Generalized source fluxes............

Using the IC Apr 2011 bound as a benchmark flux, we have, for the sum of all species,

\[ E_\nu^2 \Phi_{\nu+\bar{\nu}} = 2 \times 10^{-8} \epsilon_\pi \xi_z \quad \text{(GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}) \]

with

\[
\Phi_{\nu_e} = 6 \times 10^{-8} \left[ x \frac{1}{6} \cdot 0.6 + (1 - x) \frac{0.78}{3} \cdot 0.25 \right] \frac{1}{E_\nu^2},
\]

\[
\Phi_{\nu_\mu} = 6 \times 10^{-8} \left[ x \frac{1}{6} \cdot 0.6 + (1 - x) \frac{0.61}{3} \cdot 0.25 \right] \frac{1}{E_\nu^2} = \Phi_{\nu_\tau},
\]

\[
\Phi_{\bar{\nu}_e} = 6 \times 10^{-8} \left[ x \frac{1}{6} \cdot 0.6 + (1 - x) \frac{0.22}{3} \cdot 0.25 \right] \frac{1}{E_\nu^2},
\]

\[
\Phi_{\bar{\nu}_\mu} = 6 \times 10^{-8} \left[ x \frac{1}{6} \cdot 0.6 + (1 - x) \frac{0.39}{3} \cdot 0.25 \right] \frac{1}{E_\nu^2} = \Phi_{\bar{\nu}_\tau}.
\]
Fluxes hierarchical for p-gamma, democratic for pp sources

Mu and tau fluxes always equal for both neutrinos and anti-neutrinos irrespective of $x$ for tribimaximal mixing
Shower events in the neighbourhood of the GR...

Resonant Events....

- $\bar{\nu}_e e \rightarrow \text{hadrons}$
- $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$
- $\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau$

Non-Resonant Events....

- $\nu_e N + \bar{\nu}_e N \ (\text{CC})$
- $\nu_\tau N + \bar{\nu}_\tau N \ (\text{CC})$
- $\nu_\alpha N + \bar{\nu}_\alpha N \ (\text{NC})$
Shower and GR events for pp sources.....

$\bar{\nu}_e e \rightarrow \text{hadrons}$

$\nu_e N + \bar{\nu}_e N$ (CC)

$\nu_\alpha N + \bar{\nu}_\alpha N$ (NC)

$\nu_\tau N + \bar{\nu}_\tau N$ (CC)

$\bar{\nu}_e e \rightarrow \bar{\nu}_e e$

$\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau$

Total

$x = 1.0$, $\sin \theta_{13} = 0$
Shower and GR events for p-\gamma sources.....

x=0, sinθ_{13}=0

- $\bar{\nu}_e e \rightarrow \text{hadrons}$
- $\nu_e N + \bar{\nu}_e N$ (CC)
- $\nu_\alpha N + \bar{\nu}_\alpha N$ (NC)
- $\nu_\tau N + \bar{\nu}_\tau N$ (CC)
- $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$
- $\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau$
- Total

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Pure Lepton Tracks at the GR..................

In addition to showers, the following processes are resonant and also have distinctive signatures

\[ \bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu \]  
pure muon track with contained vertex and nothing else

\[ \bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau \]  
lollipop with contained vertex

Add them to signal calculation for GR
Muon Events

$E_\mu = 6 \text{ PeV}$  \hspace{1cm}  $E_\mu = 10 \text{ TeV}$

Measure energy by counting the number of fired PMT. (This is a very simple but robust method)
Pure muons at the GR

Pileup of muons in bins below GR energy, dictated by rapidity distribution

\[ \log_{10}(E_\mu/\text{GeV}) \]

- \( \bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu \)
- \( \nu_\mu e \rightarrow \mu \nu_e \)
Figure 17: The event spectrum of "contained lollipop" for \( x = 1 \).

\[ A = \text{effective area of the detector}, \]

\[ L_1 - L_0 = L \]

is the length of the detector,

\( x_0 \)

is the neutrino interaction point,

\( x_{\min} \)

is the minimum length to separate the \( \tau \) decay point from the \( \tau \) creation point. See Appendix B for details. We take \( A = 1 \text{ km}^2 \), \( L = 1 \text{ km} \) and \( x_{\min} = 100 \text{ m} \).

By performing the integration over \( x_0 \) and \( x \), the event rate is given by

\[
\text{Events (yr}^{-1}) = \left[ \int_{E_1}^{E_0} \nu_1 \, d \nu \int_{1}^{E_0} \nu \, d \nu + \int_{E_1}^{\infty} \nu_1 \, d \nu \int_{E_1}^{E_0} \nu \, d \nu \right] d \sigma(\bar{\nu}_e e \to \bar{\nu}_\tau \tau) \Phi(\bar{\nu}_e (E_\nu)) \times \left( (L - x_{\min} - R_{\tau}) e^{-x_{\min} R_{\tau}} + R_{\tau} e^{-L R_{\tau}} \right) \times 2 \times 10^7 \times 2\pi. \quad (5.2)
\]

A background for this signal is the non-resonant process \( \nu_\tau e \to \tau \nu_e \).

Fig. 17 and 18 show the event spectrum for \( x = 1 \) and \( x = 0 \) respectively. The signal overcomes the background, though the absolute number of events is small. Following the pure \( \mu \), we define the total number of the pure \( \tau \) event as

\[
N(\bar{\nu}_e e \to \bar{\nu}_\tau \tau) \equiv \text{Total number of events per year in } 6 < \log_{10}(E_\tau/\text{GeV}) < 7.25.
\]

5.3 Shower + pure \( \mu \) + pure \( \tau \)

Let us define the total signal of the Glashow resonance as

\[
N(\text{Shower + } \mu + \tau) \equiv N(\bar{\nu}_e e \to \text{hadrons}) + N(\bar{\nu}_e e \to \bar{\nu}_\mu \mu) + N(\bar{\nu}_e e \to \bar{\nu}_\tau \tau), \quad (5.3)
\]

† I am not sure what value of \( x_{\min} \) should be taken here. It must be less than 100 m since it must be easier to separate the \( \tau \)-decay bang from the \( \tau \) creation point than to separate the two bangs in the usual double bang. Here I take \( x_{\min} = 100 \text{ m} \) as a conservative reference.

Once tau decay is put in, number of events is small, but have a distinctive topology and negligible background.
Results........

Add conventional shower, resonant shower, pure muon and contained vertex lollipop to compute total signal

<table>
<thead>
<tr>
<th>$x$</th>
<th>(Conventional shower)</th>
<th>$GR$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.21</td>
<td>0.65</td>
<td>0.86</td>
</tr>
<tr>
<td>0.5</td>
<td>0.4</td>
<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>3.6</td>
<td>4.1</td>
</tr>
</tbody>
</table>

20, 12 and 4 events in Icecube in 5 years required to see signal from resonance depending on the relative abundance of p-gamma and p-p sources.
Signal (GR) to Background (non-resonant) comparison...........

S/B rises from 3 at x=0 to 7 at x=1
The GR and Physics beyond the SM

Due to its sensitivity to electron-antineutrinos, can the GR can provide a testing ground for some scenarios of BSM physics

Consider neutrino decay with normal hierarchy, where nu_3 and nu_2 are unstable and decay to nu_1

Then, a neutrino produced say, via a $W^\mu \bar{\nu}_i \gamma_\mu l_\beta$ vertex has a spectral flux

$$F_\nu^\beta = |U_{\beta i}|^2 AE^{-2},$$
Detection occurs via production of a charged lepton of flavour alpha, leading to

\[ F^\beta_{\nu_\alpha} = |U_{\alpha 1}|^2 |U_{\beta 1}|^2 AE^{-2} \]

In the decay scenario under consideration, the full flavour spectrum for a given species is

\[ F_{\nu_\alpha} = \sum_\beta \phi_\beta |U_{\alpha 1}|^2 |U_{\beta 1}|^2 AE^{-2}. \]

where

\[ \phi_\beta = (1, 2, 0) \]

for pp sources, for instance

Thus \[ F_{\nu_e}/F_{\nu_\mu} = |U_{\epsilon 1}|^2 /|U_{\mu 1}|^2 \sim 4. \]

which is significantly different from the expected value of 1 independent of \[ \phi_\beta \]
For the generalized flux for decay, one may write

Here \( \nu_2 \) and \( \nu_3 \) are unstable; \( \nu_{3,2} \rightarrow \nu_1 X \) and \( m_1 \ll m_2, m_3 \),

\[
E^2 F_{\nu_e}^{(\text{earth})} = 6 \times 10^{-8} |U_{e1}|^2 \left[ x \frac{C_{\nu_e}^{\nu_e}}{6} \left( \frac{0.6}{6} + (1 - x) \frac{C_{\nu_e}^{\nu_e}}{3} \right) \right],
\]

\[
C_{\nu_e}^{\nu_e} = |U_{e1}|^2 + 2|U_{\mu1}|^2 + \frac{1}{2} B_{2\rightarrow1} (|U_{e2}|^2 + 2|U_{\mu2}|^2) + \frac{1}{2} B_{3\rightarrow1} (|U_{e3}|^2 + 2|U_{\mu3}|^2),
\]

\[
C_{\nu_e}^{\nu_e} = |U_{e1}|^2 + |U_{\mu1}|^2 + \frac{1}{2} B_{2\rightarrow1} (|U_{e2}|^2 + |U_{\mu2}|^2) + \frac{1}{2} B_{3\rightarrow1} (|U_{e3}|^2 + |U_{\mu3}|^2), \quad (A.1)
\]

\[
E^2 F_{\bar{\nu}_e}^{(\text{earth})} = 6 \times 10^{-8} |U_{e1}|^2 \left[ x \frac{C_{\nu_e}^{\bar{\nu}_e}}{6} \left( \frac{0.6}{6} + (1 - x) \frac{C_{\nu_e}^{\bar{\nu}_e}}{3} \right) \right],
\]

\[
C_{\nu_e}^{\bar{\nu}_e} = C_{\nu_e}^{\nu_e},
\]

\[
C_{\nu_e}^{\bar{\nu}_e} = |U_{\mu1}|^2 + \frac{1}{2} B_{2\rightarrow1} |U_{\mu2}|^2 + \frac{1}{2} B_{3\rightarrow1} |U_{\mu3}|^2, \quad (A.2)
\]
The generalized fluxes for other flavours of \( \nu \) and antinu are then related to the electron flavour by

\[
F_{\nu_\mu} \text{(earth)} = \frac{|U_{\mu 1}|^2}{|U_{e 1}|^2} F_{\nu_e} \text{(earth)},
\]

\[
F_{\bar{\nu}_\mu} \text{(earth)} = \frac{|\bar{U}_{\mu 1}|^2}{|\bar{U}_{e 1}|^2} F_{\bar{\nu}_e} \text{(earth)},
\]

\[
F_{\nu_\tau} \text{(earth)} = \frac{|U_{\tau 1}|^2}{|U_{e 1}|^2} F_{\nu_e} \text{(earth)},
\]

\[
F_{\bar{\nu}_\tau} \text{(earth)} = \frac{|\bar{U}_{\tau 1}|^2}{|\bar{U}_{e 1}|^2} F_{\bar{\nu}_e} \text{(earth)}.
\]

We note that the flavour ratios are independent of both \( x \) and decay branching ratios \( B \).
Decay fluxes......

Figure 22: The neutrino fluxes for the decay scenario I, where $x=0.0$, $\sin \theta_{13}=0.0$

Figure 23: The neutrino fluxes for the decay scenario I, where $x=0.0$, $\sin \theta_{13}=0.2$

Figure 24: The neutrino fluxes for the decay scenario I, where $x=1.0$, $\sin \theta_{13}=0.0$

Figure 25: The neutrino fluxes for the decay scenario I, where $x=1.0$, $\sin \theta_{13}=0.2$
NH Decay Event Rates in the GR neighbourhood

Figure 27: The event spectrum for the decay scenario I with $x=0$ and $\sin\theta_{13}=0$.

Figure 28: The event spectrum for the decay scenario I with $x=0$ and $\sin\theta_{13}=0.2$.

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NH Decay Event Rates in the GR neighbourhood

Figure 25: The event spectrum for the decay scenario I with $x = 1.0$, $\sin \theta_{13} = 0$.

Figure 26: The event spectrum for the decay scenario I with $x = 1.0$, $\sin \theta_{13} = 0.2$. 

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$S/B$ ratio for the decay scenario........

Decay $S/B$ depends on $x$ but not on Branching ratios
Our predictions of UHE fluxes at Earth depend, among other things, on oscillation probabilities based on SM physics. Non-standard physics which affects the oscillation probabilities at propagation distances and energies relevant to UHE neutrinos will alter the fluxes we expect to observe. This will alter the flavour ratios and event rates, sometimes very significantly.

The WB bound for each flavour can be used to study such changes.
FIG. 1: The even-ing out of possible spectral distortions present at source due to standard oscillations over large distances as seen for hypothetical spectra of two flavours $\nu_\mu$ (deep-red) and $\nu_e$ (green) from an AGN source at a redshift $z=2$. $I(E)$ represents the flux spectrum for the two flavours.

B. Effect of neutrino decay on the flavour fluxes

A flux of neutrinos of mass $m_i$ in rest frame lifetime $\tau_i$ in energy $E$ propagating over a distance $L$ will undergo a depletion due to decay given in natural units with $c=\gamma m_i$ by a factor of $\exp(-L/E \times m_i / \tau_i)$ where $t$ is the time in the earth’s observer’s frame and $\gamma = E/m_i$ is the Lorentz boost factor. This enters the oscillation probability and introduces a dependence on the lifetime and the energy that significantly alters the flavour spectrum. Including the decay factor $n$ the probability of a neutrino flavour $\nu_\alpha$ oscillating into another $\nu_\beta$ becomes $P_{\alpha\beta} = \left| U_{\beta i} \right|^2 \left| U_{\alpha i} \right|^2 \exp(-L/\tau_i(E))$, $\alpha \neq \beta$, which modifies the flux at detector from a single source to $\phi_{\nu_\alpha} = \sum_{\beta} \phi_{\nu_\beta} |U_{\beta i}|^2 |U_{\alpha i}|^2 \exp(-L/\tau_i(E))$. We use the simplifying assumption $\tau_2^2/m_2^2 = \tau_3^2/m_3^2 = \tau/m$ for calculations involving the normal hierarchy i.e. $m_2^2 - m_1^2 = \Delta m_2^2 > 0$ and similar $\tau_1^2/m_1^2 = \tau_2^2/m_2^2 = \tau/m$ for those with inverted hierarchy i.e. $\Delta m_2^2 < 0$ but our conclusions hold irrespective of this. The total flux decreases as per Eq, which is expected for decays along the lines of Eq, and within the limitations of the assumption made in Sec. IV. An also for Eq, the assumption of complete decay leads to energy independent flux changes from the expected $\nu_d: \nu_\mu: \nu_\tau = s:s:s$ to significantly altered values depending on whether the neutrino mass hierarchy is normal or inverted as discussed in [vw]. From Fig, we note that the range of energies covered by UHE AGN fluxes spans about six to seven orders of magnitude

\textbf{Oscillations wash out spectral differences at source}
Simple Decay Scenario with Normal Hierarchy,

Depletion of $\nu_{\mu}$ and $\nu_e$ fluxes with subsequent rise

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Simple Decay Scenario with Inverted Hierarchy,

Effects (events, ratios etc.) depend on hierarchy
Changes in the WB bound for mu and tau flavours due to Lorentz Violation........

Total disappearance of tau neutrinos above a certain energy.

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Conclusions....

Icecube limits on X-Galactic UHE neutrinos have grown progressively more stringent and have made neutrino astronomy a game of very small numbers.

The Glashow resonance is a small but potentially important region which should be explored as a discovery tool for these fluxes. It seems positioned in the right energy regime given the present situation.

While the quest to understand the nature of astrophysical sources via neutrino detection is the paramount goal, it should be kept in mind that non-standard physics during propagation may affect event ratios and flavour ratios non-trivially even though sources may be “standard”.

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