Excitation of the Glashow resonance far below the PeV region

Ibragim Alikhanov

North-Caucasus Federal University
(Stavropol, Russia)

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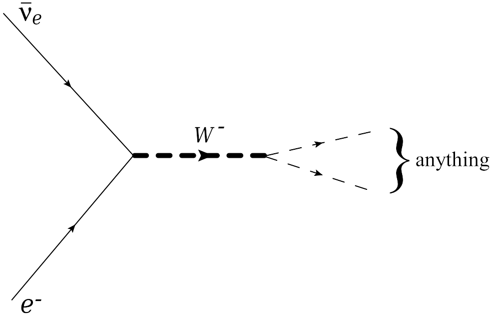
Prediction of the resonance (1959)

Glashow, *Resonant scattering of antineutrinos*, Phys. Rev. 118 (1960) 316.

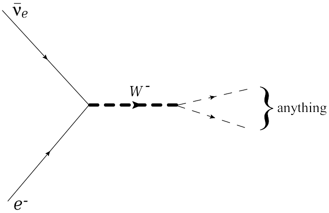
$$\bar{\nu}_e + e^- \longrightarrow W^- .$$



$$\sigma_{\bar{\nu}_e e}(s) = 24\pi \frac{\Gamma_{\bar{\nu}_e e}\Gamma}{(s - m_W^2)^2 + m_W^2\Gamma^2} .$$

Experimental problems

Using the $\bar{\nu}_e$-component of cosmic rays annihilating on electrons in matter



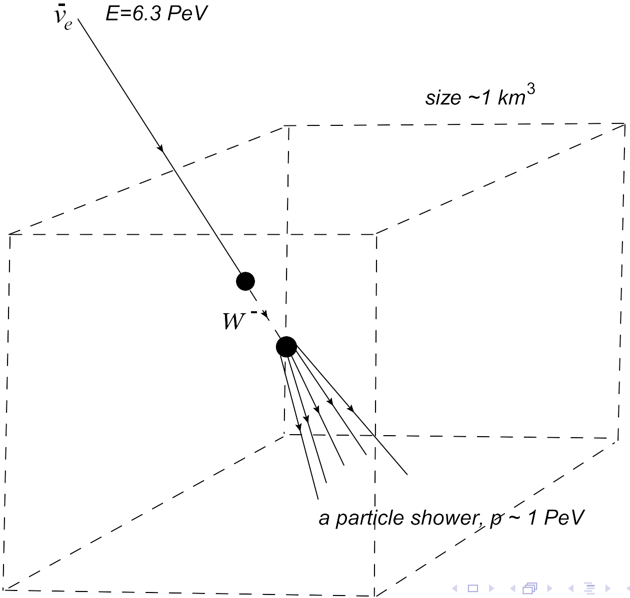
Berezinsky and Gazizov, JETP Lett. 25 (1977) 254.

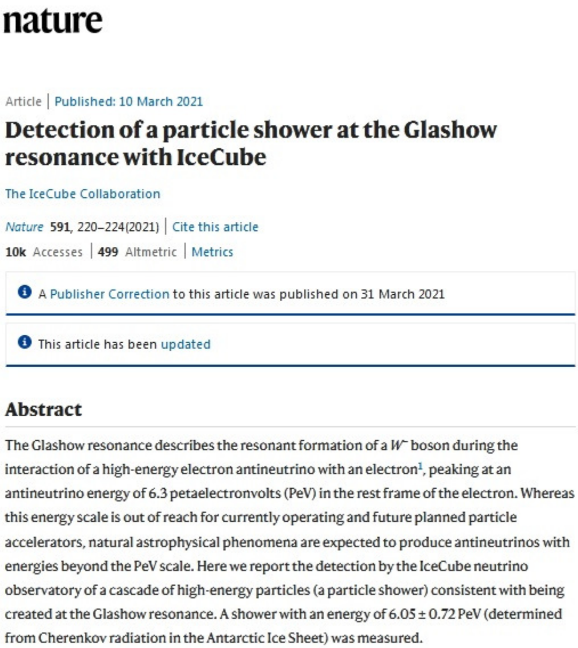
Neutrinos have to posses energies in the PeV region:

$$E_\nu = \frac{m_W^2}{2m_e} \approx 6.3 \times 10^{15}\ \text{eV} = 6.3\ \text{PeV}.$$

The corresponding neutrino flux is relatively low in this region.

Searches in large-volume water/ice detectors (IceCube, Baikal-GVD, KM3NeT)





nature

Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration

Nature **591**, 220–224(2021) | Cite this article

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A Publisher Correction to this article was published on 31 March 2021

This article has been updated

Abstract

The Glashow resonance describes the resonant formation of a W^- boson during the interaction of a high-energy electron antineutrino with an electron[1], peaking at an antineutrino energy of 6.3 petaelectronvolts (PeV) in the rest frame of the electron. Whereas this energy scale is out of reach for currently operating and future planned particle accelerators, natural astrophysical phenomena are expected to produce antineutrinos with energies beyond the PeV scale. Here we report the detection by the IceCube neutrino observatory of a cascade of high-energy particles (a particle shower) consistent with being created at the Glashow resonance. A shower with an energy of 6.05 ± 0.72 PeV (determined from Cherenkov radiation in the Antarctic Ice Sheet) was measured.

The main assertion

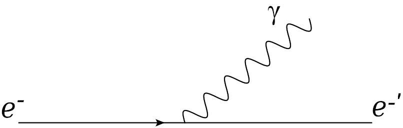
$$\bar{\nu}_e + \gamma \longrightarrow e^+ + W^- .$$

This reaction proceeds through the Glashow resonance.

I.A., PLB 741 (2015) 295.

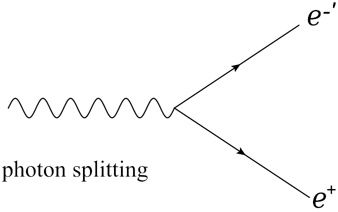
Parton distributions in QED

Kessler, Nuovo Cim. 17 (1960) 809; Baier, Fadin, Khoze, NPB 65 (1973) 381; Chen, Zerwas, PRD 12 (1975) 187.



ISR

$$f_{e/e}(x) = \frac{\alpha}{2\pi} \frac{1+x^2}{1-x} \ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right)$$

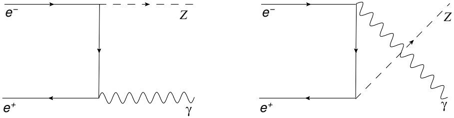


photon splitting

$$f_{e/\gamma}(x) = \frac{\alpha}{2\pi} [x^2 + (1-x)^2] \ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right)$$

The cross section for $e^+ + e^- \to \gamma + Z^0$

Berends, Burgers, Neerven, PLB 177 (1986) 191.

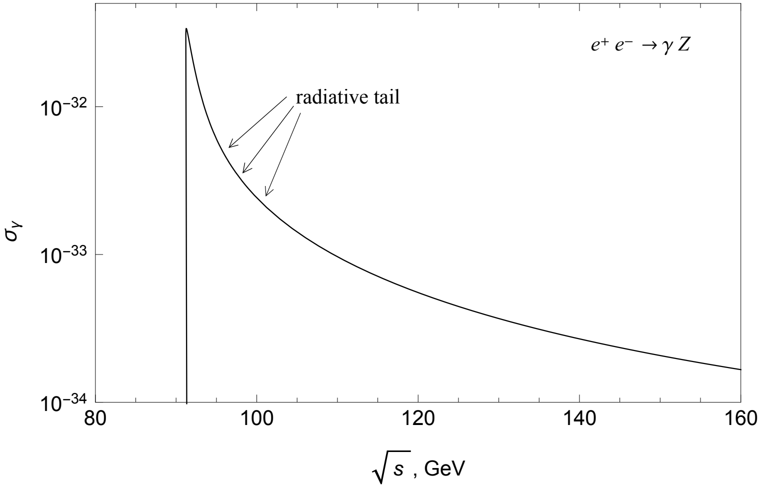


$$\sigma_{ee\to\gamma Z} = C\,\frac{\alpha}{2\pi}x\,\frac{1+x^2}{1-x}\ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right).$$

Here $C = 24\pi^2\Gamma_{Z\to ee}/m_Z^3$ and $x = m_Z^2/s$.

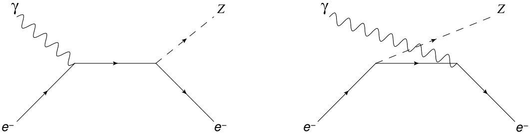
$$\boxed{\sigma_{ee\to\gamma Z} = C\,x\;f_{e/e}\left(x, Q^2\right)}$$

Initial state radiation in $e^+ + e^- \to \gamma + Z^0$



The cross section for $e^{\pm} + \gamma \longrightarrow e^{\pm} + Z^0$

Renard, Z. Phys. C 14 (1982) 209.



$$\sigma_{e\gamma\to eZ} = c\,\frac{\alpha}{2\pi}\,x\,\left[x^2 + (1-x)^2\right]\ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right).$$

Here $c = 12\pi^2\Gamma_{Z\to ee}/m_Z^3$ and $x = m_Z^2/s$.

$$\boxed{\sigma_{e\gamma\to eZ} = c\,x\;f_{e/\gamma}\left(x, Q^2\right)}$$

A comparison of the cross sections

$$\sigma(e^+e^- \to \gamma Z) \propto x\ f_{e/e}\left(x, Q^2\right),$$

$$\sigma(e^\pm\gamma \to e^\pm Z) \propto x\ f_{e/\gamma}\left(x, Q^2\right).$$

The narrow resonance Z^0 projects the PDFs onto the cross sections.

ISR in $e^+ + e^- \longrightarrow \gamma + Z^0$

The resonance is relatively narrow, $\Gamma \ll m_Z$, and one may write

$$\sigma_{ee\to Z}(s) = 12\pi \frac{\Gamma_{ee\to Z}\Gamma}{(s-m_Z^2)^2 + m_Z^2\Gamma^2} \longrightarrow C\, m_Z^2 \cdot \delta(s - m_Z^2).$$

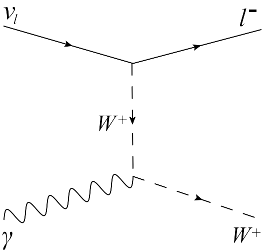
$$\sigma_{ee\to\gamma Z}(s) = \int_0^1 f_{e/e}(x,s)\sigma_{ee\to Z}(xs)dx.$$

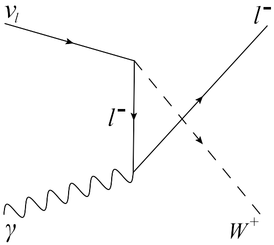
After the integration over x:

$$\boxed{\sigma_{ee\to\gamma Z}(s) = C\, \frac{m_Z^2}{s}\; f_{e/e}\left(\frac{m_Z^2}{s}\right)}$$

The cross section for $\nu_l + \gamma \to l^- + W^+$

Astrophysical implications were considered in PRL 80 (1998) 900 (Seckel).

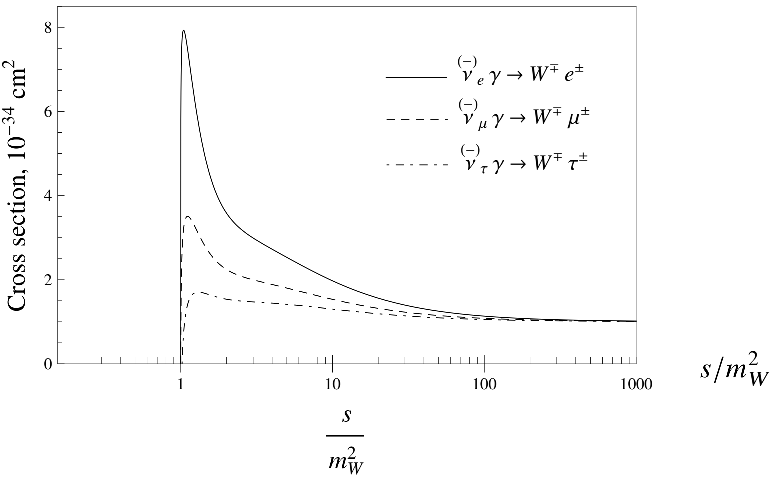




$$\sigma_{\nu\gamma\to lW} = C\frac{\alpha}{2\pi}x\left[x^2 + (1-x)^2\right]\ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right),$$

where $C = 48\pi^2\Gamma_{W\to\nu l}/m^3_W$ and $x = m^2_W/s$.

The cross sections for $\nu_l + \gamma \to l^- + W^+$



A comparison of the cross sections

$$\sigma(e^+e^- \longrightarrow \gamma Z) \propto x \; f_{e/e}\left(x, Q^2\right),$$

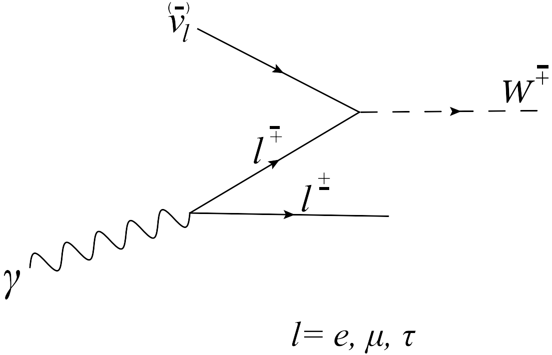
$$\sigma(e^\pm\gamma \longrightarrow e^\pm Z) \propto x \; f_{e/\gamma}\left(x, Q^2\right),$$

$$\sigma(\bar{\nu}_e\gamma \longrightarrow e^+W^-) \propto x \; f_{e/\gamma}\left(x, Q^2\right).$$

If we agree that the first two processes behave so due to the resonance than the third one, $\bar{\nu}_e\gamma \longrightarrow e^+W^-$, should be of similar nature.

A simple interpretation of $\nu_l + \gamma \to W + l$

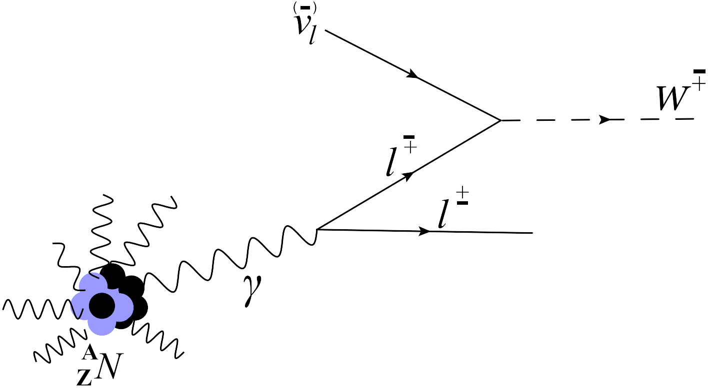
The photon acts a source of the charged leptons:



Experimental observation

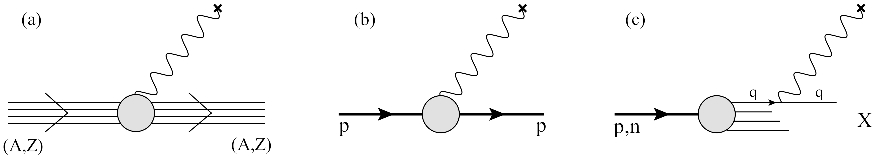
Neutrinos interacting with atomic nuclei (I.A., PLB 756 (2016) 247):

$$\bar{\nu}_e + {}^A_Z N \to {}^A_Z N + e^+ + W^-.$$

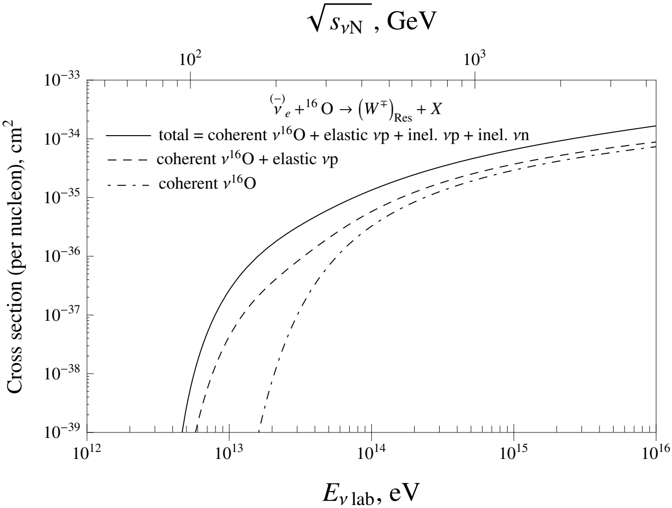


Contributions to $\nu + {}^{A}_{Z}N \to W + X$

$$\gamma(x) = \frac{1}{A}\left[\gamma_{\mathrm{coherent}}(x) + Z\gamma_{\mathrm{p\,el}}(x) + Z\gamma_{\mathrm{p\,inel}}(x) + (A-Z)\gamma_{\mathrm{n\,inel}}(x)\right],$$



The total cross sections



The number of the expected events

$$N_W = 2\pi T N_t \sum_{l=e,\mu,\tau} \int dE_\nu \, \sigma_{Nl}(E_\nu) \Phi_{\nu_l+\bar{\nu}_l}(E_\nu),$$

$$\Phi_{\nu_l+\bar{\nu}_l} = \Phi_{\nu_l+\bar{\nu}_l}^{\text{conventional}} + \Phi_{\nu_l+\bar{\nu}_l}^{\text{prompt}} + \Phi_{\nu_l+\bar{\nu}_l}^{\text{astrophysical}} .$$

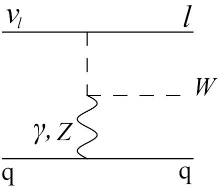
The number of the expected events

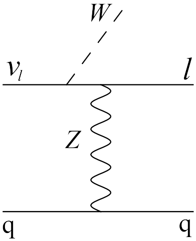
The number of W bosons produced in the resonant channel per year per 1 km^3 of water (the upper hemisphere).

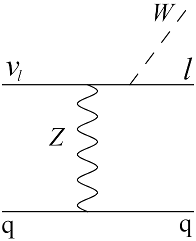
E_ν	$5 - 50$ TeV	$50 - 300$ TeV	> 300 TeV
N_W	5.2	2.3	0.6

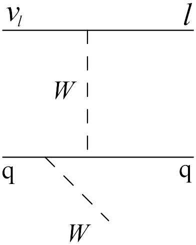
I.A., PLB 756 (2016) 247.

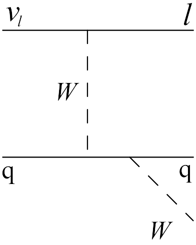
Background (non-resonant) channels





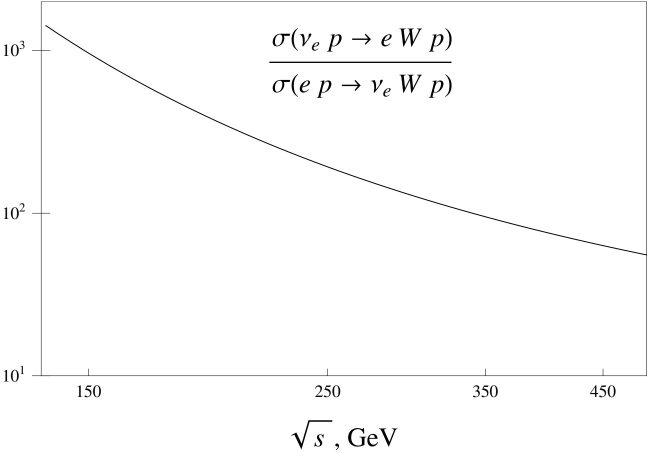






Background (non-resonant) channels

A comparison of two cross sections:



Conclusions

1. The Standard Model predicts a number of neutrino-induced resonant s-channel reactions. A method for probing these channels is proposed.
2. For instance it is shown that the reaction $\bar{\nu}_e + \gamma \longrightarrow e^+ + W^-$ proceeds through the Glashow resonance. This can be probed at neutrino energies $\sim 10 - 100$ TeV.
3. The proposed mechanism provides a way for testing CP-symmetry and the leptonic universality of the resonance. For example in $\nu_e + \gamma \to e^- + W^+$, $\nu_\mu + \gamma \to \mu^- + W^+$.
4. Detailed and independent calculations confirm that the contribution from the production of W bosons at IceCube-Gen2 can be discovered within 10 years (Zhou and Beacom, PRD 105 (2022) 093005).

Related publications

1. Mod. Phys. Lett. A 35 (2020) 2050101 [arXiv:1906.01557].
2. EPL 129 (2020) 11003 [arXiv:1812.07823].
3. Phys. Rev. D 97 (2018) 115004 [arXiv:1710.10131].
4. Phys. Part. Nucl. 49 (2018) 670.
5. Phys. Lett. B 765 (2017) 272 [arXiv:1605.04864].
6. Phys. Lett. B 756 (2016) 247 [arXiv:1503.08817].
7. Phys. Lett. B 741 (2015) 295 [arXiv:1402.6678].
8. J. Phys. G 41 (2014) 025005 [arXiv:1303.0779].
9. EPL 107 (2014) 41001 [arXiv:1204.4396].
10. Phys. Lett. B 726 (2013) 670 [arXiv:1207.1263].
11. JHEP 07 (2013) 093 [arXiv:1305.2905].
12. Phys. Lett. B 717 (2012) 425 [arXiv:1203.3631].
13. Phys. Lett. B 706 (2012) 423 [arXiv:1109.1261].
14. Phys. Lett. B 710 (2012) 149 [arXiv:1106.5414].
15. Eur. Phys. J. C 65 (2010) 269 [arXiv:0812.0937].
16. Eur. Phys. J. C 56 (2008) 479 [arXiv:0803.3707].