Novel channels with the Glashow resonance

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Based on

I.A., Phys. Lett. B 741 (2015) 295;
Phys. Lett. B 756 (2016) 247;
Mod. Phys. Lett. A 35 (2020) 2050101;
EPL 129 (2020) 11003.

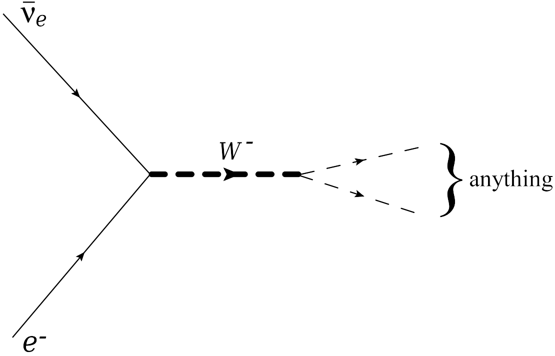
Introduction and motivation

Why are neutrinos promising in the search for new physics?

1. Neutrinos are the only known particles that had forced us to extend the Standard Model (non-conservation of the family lepton number – neutrino oscillations).
2. Difficulties associated with neutrino experiments still leave numerous "white spots".
3. There are predictions of the Standard Model not yet discovered experimentally. For example, the cosmic neutrino background and the Glashow resonance.

The Glashow resonance (GR)

Annihilation of an electron antineutrino with an electron into an on-mass-shell W^- boson: $\bar{\nu}_e + e^- \to W^-$ (Glashow, 1959).



The resonant enhancement of the $\bar{\nu}_e e^-$ scattering cross section at the pole $s = m_W^2$:

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

The Glashow resonance

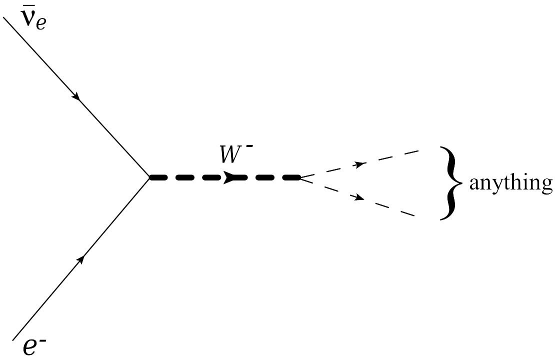
It should be emphasized that the problem is not about a plain "rediscovery" of the W boson, but about the observation of a special channel (time-like) for neutrinos in the resonance region.

For the other massive weak boson, Z^0, the corresponding channel has already been observed and under scrutiny:

$$e^+ + e^- \to Z^0 \ \ (observed).$$

$$\bar{\nu}_e + e^- \to W^- \ \ (not\ yet\ observed).$$

GR: $\bar{\nu}_e + e^- \to W^-$ (Glashow, PR 118 (1960) 316).

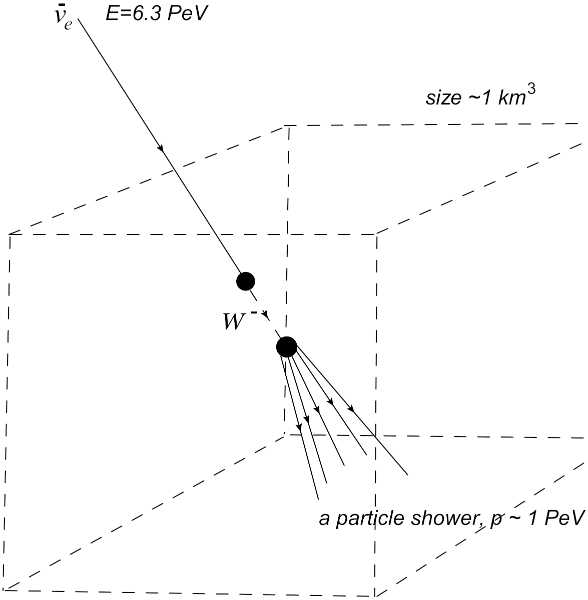


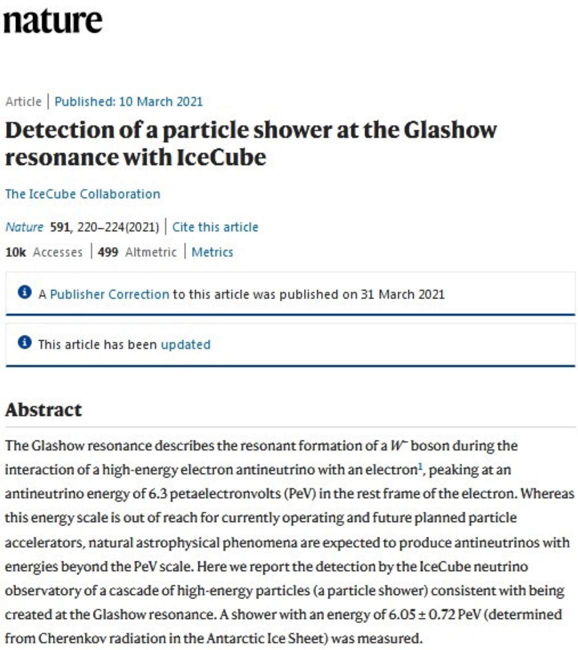
Annihilation of cosmic antineutrinos on electrons in a detector. The energy to initiate GR in the laboratory frame is

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

Currently searched for at the IceCube Neutrino Observatory.

Experimental search for the Glashow resonance





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

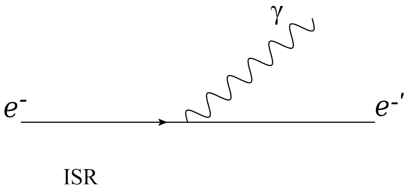
I.A., PLB 741 (2015) 295.

The following reaction proceeds through the Glashow resonance:

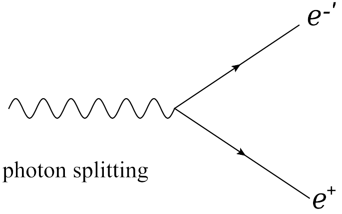
$$\bar{\nu}_e + \gamma \;\longrightarrow\; e^+ + W^-$$

QED Parton distribution functions

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



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



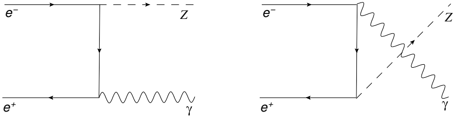
$$f_{e/\gamma}(x) = \frac{\alpha}{2\pi}\,[x^2 + (1-x)^2]\,\ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right)$$

PDFs in QED – a section talk by A. Arbuzov (today, 15:55, room 1).

Straightforward calculations of the cross sections

Consider the leading logarithmic contribution to the total cross section for (Berends, Burgers, Neerven, PLB 177 (1986) 191):

$$e^+ + e^- \to \gamma + Z^0.$$

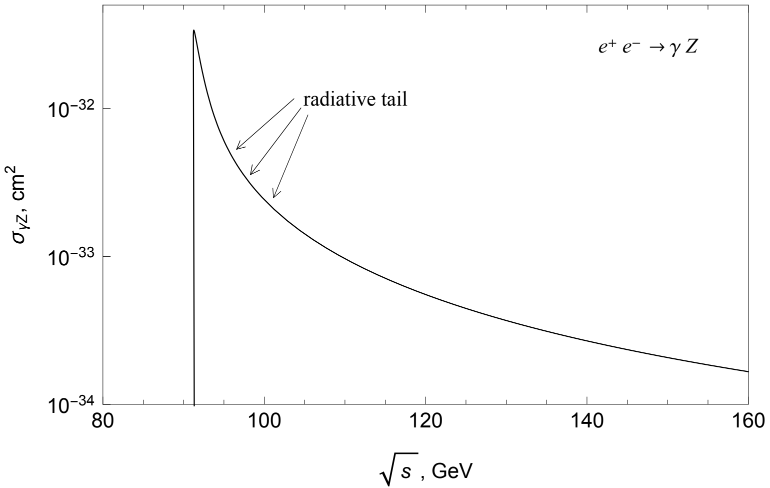


$$\sigma_{ee\to\gamma Z} = C\frac{\alpha}{2\pi}x\frac{1+x^2}{1-x}\ln\left(\frac{Q^2_{\text{max}}}{Q^2_{\text{min}}}\right).$$

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

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

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

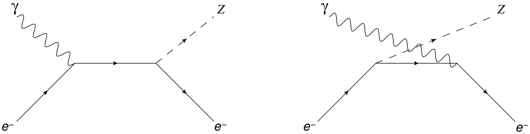


This represents the $e^+ + e^- \to Z^0$ resonance smeared out by ISR.

Straightforward calculations of the cross sections

Consider the leading logarithmic contribution to the total cross section for (Renard, Z. Phys. C 14 (1982) 209):

$$e^{\pm} + \gamma \to e^{\pm} + Z^0 .$$



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

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

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

Straightforward calculations of the cross sections

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

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

As if the resonance takes a "snapshot" of the parton distribution.

What is really going on?

The case of a narrow vector resonance in QED

If $\Gamma \ll m_R$ then the cross section for $e^+e^- \to R$ reads

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

$$e^+ + e^- \to \gamma + R.$$

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

After the integration (Chen and Zerwas, PRD 12 (1975) 187):

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

A criterion for the presence of a resonance

If $\Gamma \ll m_R$ the resonance projects out the parton distribution function into the cross section:

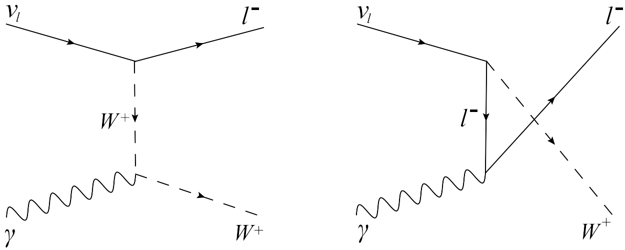
$$\boxed{\sigma_R = C \cdot x \cdot f_{e,\gamma}\left(x, Q^2\right)}$$

where C is a constant $[\mathrm{GeV}^{-2}]$, $x = m_R^2/s$.

Such a behaviour of the cross section indicates the presence of an underlying resonant process.

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

First studied: Seckel, PRL 80 (1998) 900.



The leading contribution reads (I.A., PLB 741 (2015) 295)

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

where $C = 48\pi^2\Gamma_{W\to\nu l}/m_W^3$ and $x = m_W^2/s$. Again, the presence of the QED PDF (the photon splitting function) is explicit.

One more resonance

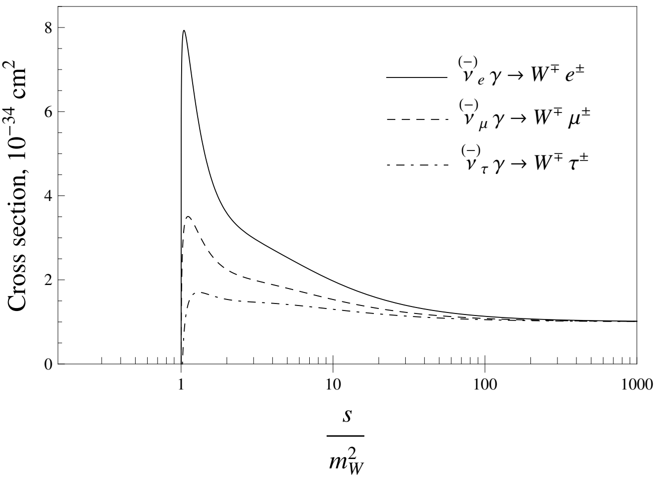
$$\sigma(e^+e^- \to \gamma Z) \propto x\, f_{e/e}\left(x, Q^2\right),$$

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

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

A comparison of these cross sections is self explanatory, suggesting the resonant W^- boson production channel in $\bar{\nu}_e\gamma \to e^+W^-$.

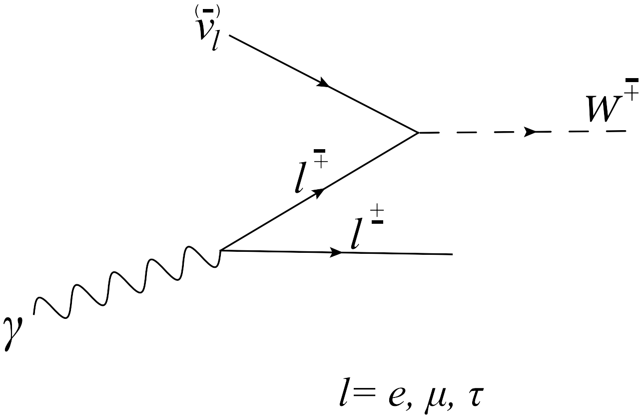
The cross sections for $\nu_l + \gamma \to l^- + W^+$



s/m_W^2

The photon as a source of the charged leptons

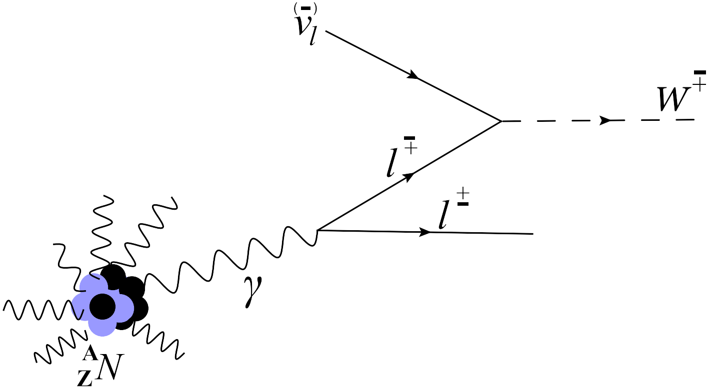
An intuitive view of the underlying resonant mechanism.
This is similar to ISR:



Neutrino–nucleus scattering

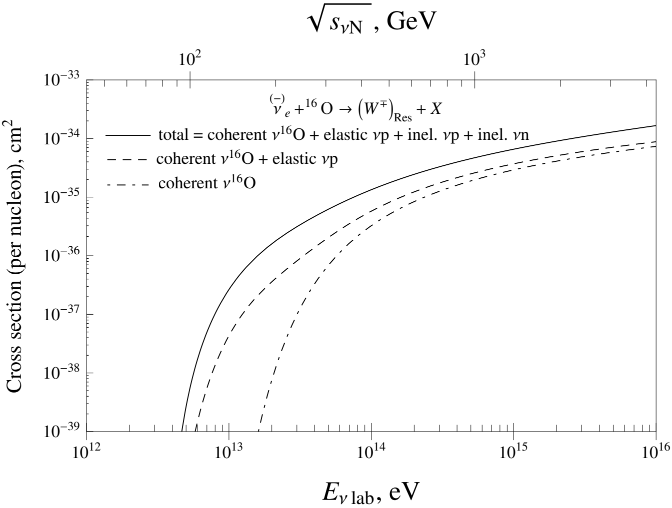
An atomic nucleus provides a source of the Weizsäcker–Williams equivalent photons, so that the Glashow resonance should appear in high energy neutrino–nucleus scattering (I.A., PLB 756 (2016) 247):

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

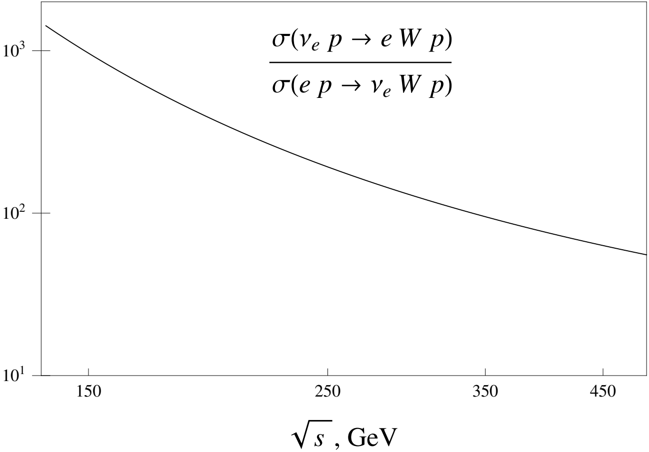


In km-scale neutrino telescopes, water serves as a target and oxygen is abundant in their volumes. IceCube, Baikal-GVD, KM3NeT.

$$\bar{\nu}_e + {}^{16}\mathrm{O} \to {}^{16}\mathrm{O} + e^+ + W^-.$$



A comparison of two cross sections within the Standard Model (I.A.,PLB 756(2016)247):



Summary

1. Resonant channels of the W boson production in $\nu\gamma$ interactions within the standard electroweak theory are considered.
2. For example, it is shown that the reaction $\bar{\nu}_e + \gamma \to e^+ + W^-$ proceeds through the Glashow resonance.
3. The resonant scenario can be probed for all the three neutrino flavors, ν_e, ν_μ, ν_τ.
4. The corresponding cross sections for the excitation of the resonance on ^{16}O are calculated. The results may be useful for interpreting experimental data at large volume neutrino telescopes as IceCube, Baikal-GVD and KM3NeT.
5. The presented procedure can be applied to the production of other scalar and/or vector narrow resonances.

Backup

The widths of $W^{\pm}$ bosons are relatively narrow, $\Gamma/m_W \propto 10^{-2}$, so that the $\delta(s - m_W^2)$-approximation holds.

Consider the following reaction (Seckel, PRL 80 (1998) 900):

$$\nu_e + \gamma \to e^- + W^+.$$

It turns out that the corresponding cross section in the leading logarithmic order behaves as (I.A., PLB 741 (2015) 295)

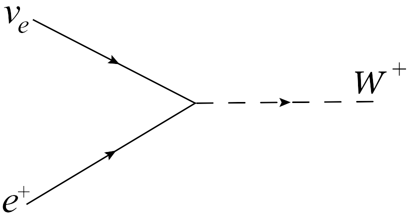
$$\sigma_{\nu_e \gamma \to eW}(s) = C' \cdot \frac{m_W^2}{s} f_{\gamma/e}\left(\frac{m_W^2}{s}\right).$$

This is a clear indication that the reaction above proceeds through a resonant mechanism of the production of W^+.

The CP conjugate of the Glashow resonance

What about the following reaction:

$$\nu_e + e^+ \to W^+?$$



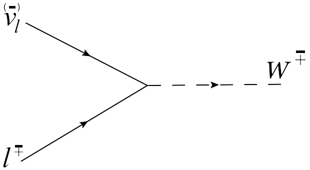
Where can one get a target with positrons?

The Glashow resonance with other leptons

Going farther, one may wonder whether it is possible to probe the lepton universality for the resonance:

$$\nu_\mu + \mu^+ \to W^+, \;\; \nu_\tau + \tau^+ \to W^+.$$

$$\bar{\nu}_\mu + \mu^- \to W^-, \;\; \bar{\nu}_\tau + \tau^- \to W^-.$$



Targets with μ and τ are also needed.