DETECTION OF A PARTICLE SHOWER AT THE GLASHOW RESONANCE WITH ICECUBE

PRESENTED BY ZAMIUL ALAM

Photo Credit: Sven Lidstrom, IceCube/NSF
WHAT IS GLASHOW RESONANCE?

Picture of Sheldon Glashow

https://www.nobelprize.org/prizes/physics/1979/glashow/biographical/
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1. Glashow, S. L. Resonant Scattering of Antineutrinos. Phys. Rev. 118, 316–317 (1960).
WHO IS SHELDON GLASHOW?
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The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current."

https://www.nobelprize.org/prizes/physics/1979/summary/
BACK TO GLASHOW RESONANCE

Credit: IceCube Collaboration
\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X

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The cross-section becomes resonantly enhanced for a centre-of-mass energy $\sqrt{s} = M_W = 80.38$ GeV
\[ \sigma(s) = 24\pi \Gamma_W^2 \cdot B_{W^{-}\rightarrow \bar{\nu}_e+e^-} \cdot \frac{s/M_W^2}{(s - M_W^2)^2 + \Gamma_W^2 M_W^2} \]
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2. Barger, V. et al. Glashow resonance as a window into cosmic neutrino sources. Phys. Rev. D90, 121301. arXiv: 1407.3255 [astro-ph.HE] (2014)
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GLASHOW RESONANCE

BACK TO GLASHOW RESONANCE

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The resonance energy lies beyond terrestrial accelerators, but not astrophysical sources of neutrinos.
WHICH BRINGS US TO ICECUBE

Credit: Martin Wolf, IceCube/NSF
CHERENKOV RADIATION

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Cherenkov Radiation is electromagnetic radiation emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the phase velocity (speed of propagation of a wavefront in a medium) of light in that medium. [3]

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3. Jackson, John David (1999). Classical Electrodynamics (3rd ed.)

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The IceCube Laboratory (ICL)

Credit: IceCube Collaboration
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ICECUBE DETECTION PRINCIPLE

The last DOM

Credit: Robert Schwarz, NSF
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- IceCube has a timing resolution of 2 ns.
DETECTION OF GLASHOW RESONANCE
A machine-learning-based algorithm was run to obtain a sample of PeV energy partially contained events (PEPEs).
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One event was detected on 2016 December 8 at 01:47:59 UTC (Coordinated Universal Time) with visible energy greater than 4 PeV.
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But accounting for systematic uncertainties in photon propagation due to the ice model—scattering and absorption lengths of light in the ice and the overall detector calibration, the visible energy of the event is $6.05 \pm 0.72$ PeV.
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But accounting for systematic uncertainties in photon propagation due to the ice model—scattering and absorption lengths of light in the ice and the overall detector calibration, the visible energy of the event is $6.05 \pm 0.72$ PeV.

This is consistent with a 6.3 PeV $W^-$ that decays hadronically.
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After reconstruction, the three DOMs closest to the reconstructed vertex were found to have detected pulses earlier than is possible for photon traveling in ice at $v = 2.19 \times 10^8 ms^{-1}$. 
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Such pulses can, however, be produced by muons created from meson decays in the hadronic shower, which travel close to the speed of light in vacuum.
a. Schematic of an escaping muon traveling at faster than the speed of light.
b. Event view, showing DOMs that triggered across IceCube at a later time.
c. Distributions of the deposited charge over time on DOM 54.
d. Distributions of the deposited charge over time on DOM 55.
The 90% contours from the cascade (red) and hybrid cascade+track (blue) directional reconstructions are shown in equatorial coordinates. The most-probable direction according to the hybrid reconstruction is shown as the purple star.
A second reconstruction using only the early pulses to fit a track hypothesis further improves and verifies the directional reconstruction of this event.

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**DIRECTIONAL RECONSTRUCTION**

- A second reconstruction using only the early pulses to fit a track hypothesis further improves and verifies the directional reconstruction of this event.

- This indicates that the muons and hadronic shower travel along the same general direction, as is expected from relativistic kinematics.

The 90% contours from the cascade (red) and hybrid cascade+track (blue) directional reconstructions are shown in equatorial coordinates. The most-probable direction according to the hybrid reconstruction is shown as the purple star.
DETECTION OF GLASHOW RESONANCE

NOT OF ATMOSPHERIC ORIGIN
The only possibility for a cosmic-ray-induced atmospheric muon to produce both a 6PeV cascade and early pulses, as in this event, is for it to reach IceCube at PeV energies and deposit nearly all its energy over a few meters.
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By requiring that muons deposit a visible energy similar to that of the cascade over a short distance, but retain the energy allowed by early pulses, the background muon flux gives an expectation rate of $1.1 \times 10^{-7}$ events in 4.6 years.
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Similarly, the early pulse signature can be used to reject the atmospheric neutrino background hypothesis.
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The expectation rate of atmospheric neutrinos passing the PEPE event selection with accompanying muon energy consistent with the observed early pulses is around $2 \times 10^{-7}$ in 4.6 years.
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The expectation rate of atmospheric neutrinos passing the PEPE event selection with accompanying muon energy consistent with the observed early pulses is around $2 \times 10^{-7}$ in 4.6 years.

We conclude that the event is induced by an astrophysical neutrino and is not of atmospheric origin.
BACKGROUNDS
The major backgrounds to the Glashow resonance are charged-current (CC) interactions (mediated by the exchange of a virtual $W^\pm$) of electron (anti)neutrinos with nucleons.
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While the amount of early Cherenkov light is consistent with the leading muon energy expected from a hadronic shower at the Glashow resonance (6.3 PeV), it is an order of magnitude above that expected from a CC electron neutrino interaction at those energies.
Expected Monte Carlo (MC) event distributions in visible energy of hadrons from $W^-$ decay (GR h., blue), the electron from $W^-$ decay (GR e., orange), charged-current interactions (CC; red) and neutral-current interactions (NC; green) for a live-time of 4.6 years from the PEPE sample.
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While an NC shower is purely hadronic, a much higher incoming neutrino energy is required. The steeply falling power-law flux of astrophysical neutrinos results in suppression of the NC background.
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- Thus, it really was a particle shower at the Glashow Resonance.
FUTURE ENDEAVORS

Credit: IceCube/NSF
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- A high-energy in-ice array
- A surface air shower array with additional veto capabilities
- A low-energy in-ice infill array (the Precision IceCube Next Generation Upgrade, or PINGU)
- And potentially a shallow sub-surface array of radio antennas

Credit: IceCube/NSF
ICECUBE COLABORATION

The IceCube Collaboration is made up of over 400 scientists from 53 institutions in 12 countries around the world.

Credit: IceCube Collaboration
THANKS TO THE ICECUBE COLLABORATION! AND THANK YOU!