The Elusive Neutrino

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1. What are neutrinos
   - Aspects of neutrinos
   - A brief history of neutrinos

2. Recent discoveries in neutrinos
   - Atmospheric neutrino puzzle
   - Solar neutrino puzzle

3. The future of neutrino physics
   - What we know about neutrinos
   - What we do not know about neutrinos
   - What we are doing about it
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What are neutrinos

- Particles that accompany radioactive $\beta$ decay
  - Byproducts of nuclear reactions
  - The most abundant particles
  - The most weakly interacting particles
  - The lightest massive particles
  - Particles that break left-right (mirror) symmetry maximally
  - Particles that may be their own antiparticles
  - Particles that may have created the matter-antimatter asymmetry
  - Particles that have always sprung surprises
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The Standard Model of Particle Physics

- 3 neutrinos: $\nu_e, \nu_\mu, \nu_\tau$
- chargeless
- spin 1/2
- almost massless
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Neutrinos postulated but unobserved: 1932 – 1956

- Beta decay: $^{A}_{Z}N \rightarrow ^{A}_{Z+1}N + e^{-}$

- In any two-body decay, energy of final products is fixed.

- $\Rightarrow$ Electron should have a fixed energy

- Energy-momentum conservation in grave danger!!

- A reluctant solution (Pauli): postulate a new particle
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Discoveries of neutrinos

- **Electron neutrino $\nu_e$: 1956**
  - Reines-Cowan: Nobel prize 1995
  - Reactor neutrinos: $\bar{\nu}_e + p \rightarrow n + e^+$
  - $e^+ + e^- \rightarrow \gamma + \gamma$ (0.5 MeV each)
  - $n + ^{108}\text{Cd} \rightarrow ^{109}\text{Cd}^* \rightarrow ^{109}\text{Cd} + \gamma$ (delayed)

- **Muon neutrino $\nu_\mu$: 1962**
  - Steinberger-Schwartz-Lederman: Nobel prize 1988
  - Neutrinos from pion decay: $\pi^- \rightarrow \mu^- + \nu(\mu)$
  - $\nu(\mu) + N \rightarrow N' + \mu^-$
  - Always a muon, never an electron/positron

- **Tau neutrino $\nu_\tau$: 2000 (Fermilab)**
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Neutrinos from cosmic rays

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- “$\nu_\mu$” flux = $2 \times$ “$\nu_e$” flux
- Flux should be isotropic
Neutrinos from cosmic rays

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"$\nu_\mu$" flux = 2× "$\nu_e$" flux

Flux should be isotropic
Zenith angle dependence

Sub-GeV $e$-like

Sub-GeV $\mu$-like

Multi-GeV $e$-like

Multi-GeV $\mu$-like + PC
Atmospheric neutrino “oscillations”

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

(\(\Delta m^2 \equiv m^2_{\nu_1} - m^2_{\nu_2}\))

- Wavelength \(\sim\) Earth diameter
- \(\nu_e\) do not take part in the oscillations
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How does the Sun shine

- Nuclear fusion reactions: mainly \( ^1_4 H \rightarrow ^2_4 He + 2e^+ + 2\nu_e \)
- Light cannot be produced unless neutrinos are produced !!
- Davis-Koshiba Nobel prize 2002
Mystery of missing solar neutrinos

Where did the missing neutrinos go?
Solar $\nu_e$ convert to $\nu_\mu$ and $\nu_\tau$
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Our current knowledge about neutrinos

- $\nu_e, \nu_\mu, \nu_\tau$ mix among each other
- Atmospheric neutrinos:
  $\Delta m^2_{\text{atm}} \approx 2 \times 10^{-3} \text{ eV}^2$, $\theta_{\text{atm}} \approx 45^\circ$
- Solar neutrinos:
  $\Delta m^2_{\odot} \approx 8 \times 10^{-5} \text{ eV}^2$, $\theta_{\odot} \approx 32^\circ$
- Reactor neutrinos:
  the “third” angle: very small ($\theta_{13} < 12^\circ$, may even be zero).
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Open questions in neutrino physics

- Mass hierarchy: Normal or Inverted? (red $\nu_e$, green $\nu_\mu$, blue $\nu_\tau$)

- Absolute neutrino masses
- Are there more than 3 neutrinos?
- CP violation? Own antiparticles? ...
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Ongoing activities in neutrino physics

- **Solar experiments**: measuring the energy of the sun in neutrinos
- **Reactor / short baseline experiments**: Measuring the small mixing angle $\theta_{13}$, confirming atmospheric oscillations with known $\nu$ fluxes
- **“Neutrino factories”**: Long baseline experiments that span the Earth
- **Neutrino telescopes**: Looking for extremely energetic neutrinos from the cosmic rays
- **Supernova Neutrinos**: Core collapse and explosion of a massive star
- **India-based Neutrino Observatory (INO)**: Atmospheric and long baseline experiments
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