Solar neutrinos: the problem and its solution

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September 30, 2015
Discovery of radioactivity

- Becquerel: discovery of radioactivity in uranium salts
- Rutherford: $\alpha$ and $\beta$ radioactivity
- Curies: discovery of polonium and radium
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α, β, and γ radioactivity

The are Three Types of Radioactive Decay
3 October 2009

\[ A \longrightarrow B + \text{radiation } \alpha/\beta/\gamma \]

\[ M_A c^2 = M_B c^2 + E_{\text{radiation}} + (B \text{ kinetic energy}) \]

- **α**: nucleus of helium atom (2 p and 2 n)
- **β**: energetic electron
- **γ**: energetic electromagnetic radiation
Conservation of energy in $\beta$ decay: a problem

- Chadwick: electron in $\beta$ decay emerges with a continuum spectrum of kinetic energies.
- Conservation of energy appears to be violated:

$$T_e \simeq M_A c^2 - M_B c^2 - M_e c^2$$

- Bohr: principle may not be valid in atomic phenomena.
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Pauli’s proposal

- Pauli: additional particle emitted in $\beta$ decay
  \[ A \rightarrow B + e^- + x \]
  \[ T_e + E_x \approx M_A c^2 - M_B c^2 - M_e c^2 \]

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Fermi’s theory

- **Fermi: in nucleus the process** \( n \rightarrow p + e^- + \bar{\nu}_e \) **occurs**

- **Fermi calls the \( x \) particle “neutrino”**
Weak interaction

- Transformation $n \rightarrow p$ caused by a new interaction, the “weak interaction”
- The “strong interaction” binds protons and neutrons in the nucleus
- Gravitational and electromagnetic interactions act on large distances (familiar to us from our everyday life)
- The strong and weak interactions act on distances of the order $10^{-13}$ cm $\ll$ atom size of $10^{-8}$ cm
- Bethe and Peierls calculate probability for
  
  $A + \nu_e \rightarrow B + e^-$ (from Fermi’s theory)
  
  and conclude there is “…no practically possible way of observing the neutrino”
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Detecting $\nu$'s: Pontecorvo's proposal

- Identify copious source of neutrinos: a nuclear reactor produces $\sim 10^{13}$ neutrinos/sec/cm$^2$.
- Pontecorvo: use cleaning fluid (C$_2$Cl$_4$) and the reaction
  \[ ^{37}\text{Cl} + \nu_e \longrightarrow ^{37}\text{Ar} + e^- \]
  and detect products from radioactive decay of $^{37}\text{Ar}$.
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Detecting $\nu$’s: Reines and Cowan’s proposal

- **Reines and Cowan**: use the reaction (also predicted by Fermi’s theory)

$$A Z + \bar{\nu}_e \longrightarrow A(Z - 1) + e^+$$

and detect positron ($e^+$)

- Experiment facilitated by recent discovery of organic fluids which scintillate
Fig. 1. The first conceptual proposed experiment to detect the free neutrino. This experiment was approved by the authorities at Los Alamos but was superseded by the approach which used a fission reactor as a neutrino source and the delayed coincidence reaction to reduce the background.
Neutrinos from nuclear reactor

Problem: background from cosmic rays

Solution: detect $e^+$ and $n$ created by weak interactions

Irrefutable proof that neutrinos exist in 1956!
It is discovered that one Helium atom is slightly less massive than four Hydrogen atoms ($\Delta M$).

Eddington: nuclear reactions are responsible for energy production in the Sun ($E = \Delta M \cdot c^2$).

Bethe proposes the sequence of reactions:

\[ p + p \rightarrow d + e^+ + \nu_e; \quad p + d \rightarrow ^3\text{He} + \gamma; \quad ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + p + p \]

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The Sun as a source of neutrinos

- The previous sequence of reactions converts
  \[ 4p + 2e^- \rightarrow ^4\text{He} + 2\nu_e + (\gamma \text{ radiation}) \]

  and releases the energy
  \[ E_\gamma = \left[ 4\, M(^1\text{H}) + 2\, M_e - M(^4\text{He}) \right] c^2 - 2 \langle E_{\nu_e} \rangle \]
  \[ \simeq 26.7 \text{ MeV} \left( 4.3 \times 10^{-12} \text{ J} \right) \]

- Sun luminosity is \( L_\odot \simeq 3.8 \times 10^{26} \text{ J} \cdot \text{s}^{-1} = 3.8 \times 10^{17} \text{ GW} \)

  \[ N_{\nu_e} \simeq 2 \times L_\odot / \left( 4.3 \times 10^{-12} \text{ J} \right) \simeq 1.8 \times 10^{38} \text{ s}^{-1} \]

- The neutrino flux on Earth due to \( pp \) weak fusion is
  \[ \phi(pp) \simeq N_{\nu_e} / (4 \pi D^2) \simeq 6.4 \times 10^{10} \text{ neutrinos/(cm}^2 \cdot \text{s)} \]

  where \( D = 1.5 \times 10^8 \text{ km} \) is the distance Earth-Sun
Detecting solar $\nu_e$

Davis sets up tank with $3.8 \times 10^5$ liters of C$_2$Cl$_4$ at a depth of 1.5 km in Homestake mine to detect $^{37}$Ar from

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but $\nu_e$'s due to pp fusion have too low $E_{\nu_e}$ to activate it.

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Bahcall develops “standard solar model” (SSM) and estimates $\nu_e$ fluxes from reactions in $pp$ chain.

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The solar neutrino problem

- **Davis** announces first results in 1968: only 1/3 of expected $\nu_e$ from SSM are detected
- Doubts on (i) *Davis’* ability to count a few $^{37}$Ar atoms out of $10^{30}$ atoms in tank and (ii) validity of Bahcall’s SSM
- *Davis’* first results were later confirmed over two decades of running!
- A different experiment (Kamiokande, 1989) confirms $\nu_e$ deficit observed by Davis
In late 80’s a new experiment, Kamiokande (K), comes online, later upgraded to Super-Kamiokande (SK)

- **SK detector:** \(~ 50 \text{ ktons of pure water and } \sim 11,000\) photomultipliers (PMT’s)
SK: a picture with installed PMT’s

- Stainless steel cylindrical container (∼39 m diameter and ∼41 m height)
Solar neutrinos

Radioactivity

Theory of $\beta$ decay

Neutrinos

How the Sun shines

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Neutrino flavors

The solution

SK: a picture with nearly filled tank

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo
K experiment confirms Davis’ results

- A $\nu_e$ collides with $e^-$ in water molecule and propels it forward
- Fast $e^-$ produces cone of light (Cherenkov radiation) along its path
- $K$ can infer direction and energy of incoming $\nu_e$ from direction and intensity of Cherenkov light
- In 1989 $K$ announces that $\nu_e$’s come from the Sun and confirms deficit observed by Davis
K experiment confirms Davis’ results

Elusive Particles Continue to Puzzle Theorists of the Sun

By GEORGE JOHNSON
Published: June 9, 1998

ONE of the biggest embarrassments of 20th-century science -- the sun’s refusal to emit nearly as...
The Standard Model and neutrino flavors

- There are three neutrino flavors: $\nu_e$, $\nu_\mu$, and $\nu_\tau$ (and their three antiparticles: $\bar{\nu}_e$, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$)

$$\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e \quad \tau_\mu \simeq 2.2 \times 10^{-6}\text{s}$$

- $\nu_\mu$ and $\nu_\tau$ discovered, respectively, in 1962 and 2000
Pontecorvo’s insight: neutrinos have mass and oscillate between flavors, for example $\nu_e \rightarrow \nu_\mu$ or $\nu_e \rightarrow \nu_\tau$.

Only $\nu_e$’s are produced by the Sun and can be detected in Davis’ experiment, while $\nu_\mu$ and $\nu_\tau$ escape detection.

How do oscillations occur? In Quantum Mechanics (QM) particles can also be described by waves:

$$\lambda = h/p \quad h = \text{Planck constant} \quad p = mv \text{ momentum}$$
Neutrino flavor oscillations I

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- **How do oscillations occur?** In Quantum Mechanics (QM) particles can also be described by waves

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In the case of two flavors, for simplicity, QM predicts

\[ P_{\nu_e \rightarrow \nu_\mu}(x) = \sin^2(2\theta) \sin^2 \left( \frac{\pi x}{L} \right) \text{ with } L = \frac{2 \hbar c^3}{m_2^2 - m_1^2} \]

Presence of matter (electrons in solar interior) modifies \( P_{\nu_e \rightarrow \nu_\mu}(x) \) and enhances oscillations (MSW effect)
Evidence accumulates that neutrinos oscillate: SK measures $\nu_e$'s and $\nu_\mu$'s due to cosmic rays

$$\frac{\#\nu_\mu}{\#\nu_e} \approx 1 \text{ versus expected } \approx 2$$

Variation of $\nu_\mu$ flux with zenith angle
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Variation of $\nu_\mu$ flux with zenith angle
The Sudbury Neutrino Observatory (SNO)

- 1,000 tons of heavy water ($D_2O$) and 9,600 PMT’s mounted on a geodesic support structure
- SNO detects neutrinos via the processes:
  
  \[ d + \nu_e \rightarrow p + p + e^- \quad d + \nu_x \rightarrow p + n + \nu_x \]
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The SNO experiment
The SNO results: the solar $\nu_e$ problem solved!

- $\nu_e$ flux: CC from reaction $d + \nu_e \rightarrow p + p + e^-$
- mostly $\nu_e$ flux: ES from $e^- + \nu_e \rightarrow e^- + \nu_e$
- $\nu_e + \nu_\mu + \nu_\tau$ flux: NC from $d + \nu_x \rightarrow p + n + \nu_x$
Summary

- The solar neutrino problem: the story of a triumph!
- The physics of neutrinos is now a field of intense research activity:
  - determination of $\Delta m_{ij}^2$ and $\theta_{ij}$
  - role of neutrinos in supernova explosions
  - neutrinos and the matter-antimatter asymmetry problem
  - ...
- The support of the U.S. Department of Energy under contract DE-AC05-06OR231 is gratefully acknowledged
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$\nu$ squared-mass splitting and mixing angle