Solar neutrinos: the problem and its solution

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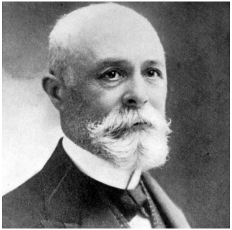
Discovery of radioactivity

- Becquerel: discovery of radioactivity in uranium salts
- Rutherford: α and β radioactivity
- Curies: discovery of polonium and radium

Discovery of radioactivity



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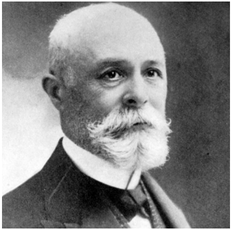

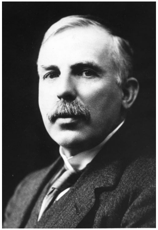

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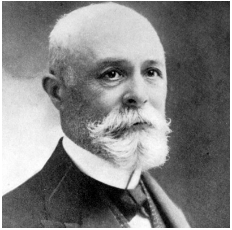

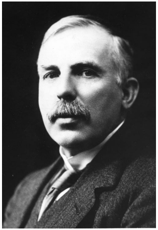

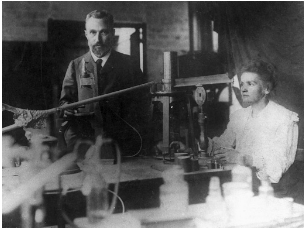

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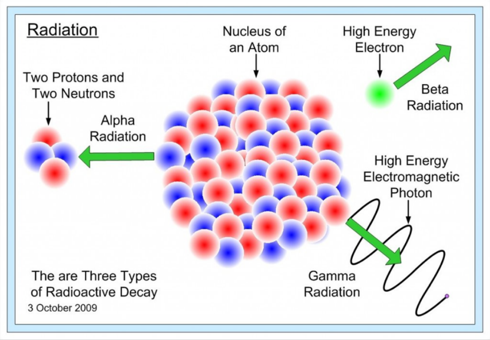
α, β, and γ radioactivity



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

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

- α: nucleus of helium atom (2 p and 2 n)
- β: energetic electron
- γ: energetic electromagnetic radiation

Conservation of energy in β decay: a problem

- Chadwick: electron in β 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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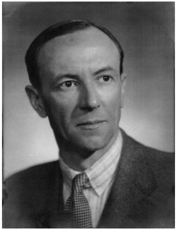

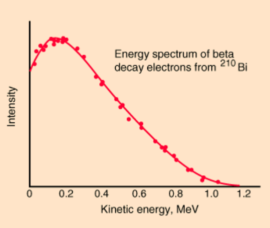

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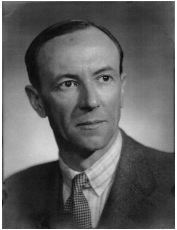

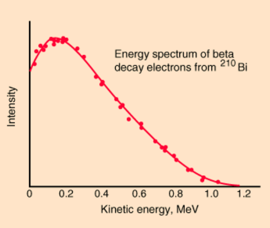

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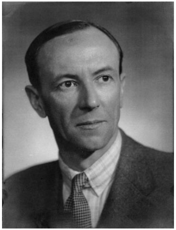

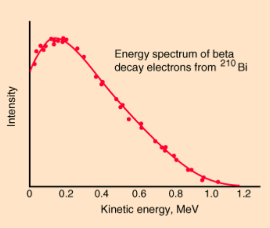

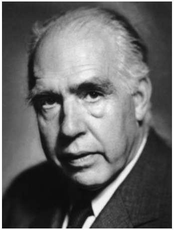

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Pauli's proposal

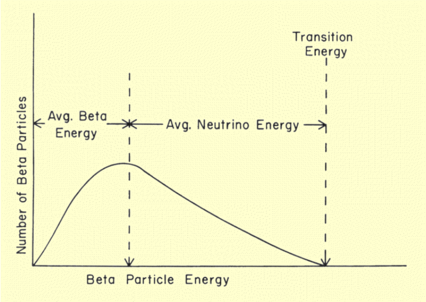
- Pauli: additional particle emitted in β decay

$$A \longrightarrow B + e^- + x$$

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

- x particle must be neutral and lighter than the electron

Pauli's proposal



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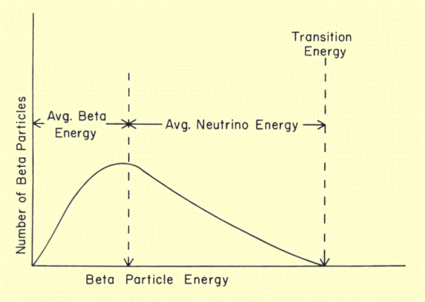

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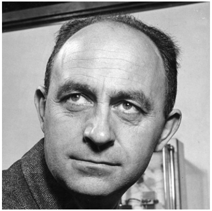
Fermi’s theory



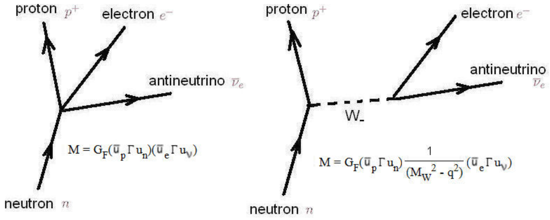
Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

- Fermi: in nucleus the process $n \longrightarrow p + \mathrm{e}^- + \overline{\nu}_\mathrm{e}$ occurs



a. Fermi's 4-point Interaction, 1934 b. Weak Interaction mediated by boson, 1938

- Fermi calls the x particle “neutrino”

Weak interaction

- Transformation $n \to p$ 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

$$A + \nu_e \longrightarrow B + e^- \quad \text{(from Fermi's theory)}$$

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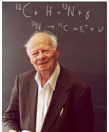

Detecting ν's: Pontecorvo's proposal

- Identify copious source of neutrinos: a nuclear reactor produces $\sim 10^{13}$ neutrinos/sec/cm^2
- Pontecorvo: use cleaning fluid (C_2Cl_4) and the reaction

$$^{37}\mathrm{Cl} + \nu_e \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

  and detect products from radioactive decay of ^{37}Ar
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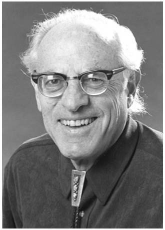
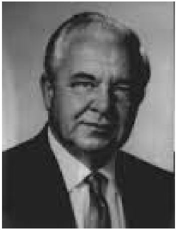
Detecting ν's: Reines and Cowan's proposal





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

$$^{A}Z + \overline{\nu}_{\mathrm{e}} \longrightarrow {}^{A}(Z-1) + \mathrm{e}^{+}$$

and detect positron (e^{+})

- Experiment facilitated by recent discovery of organic fluids which scintillate

A suitable neutrino source!

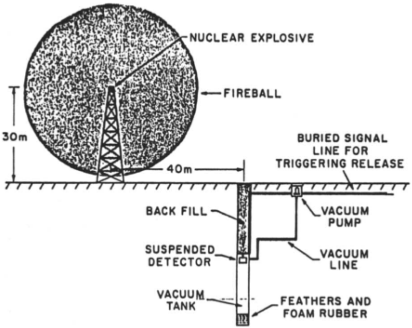
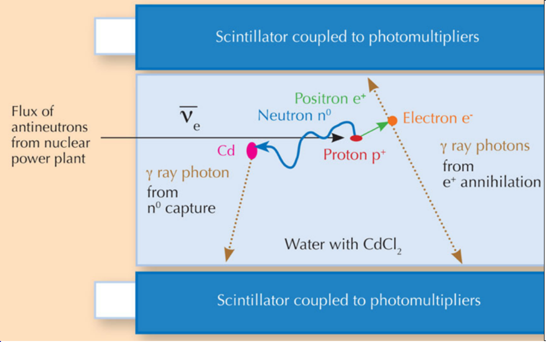
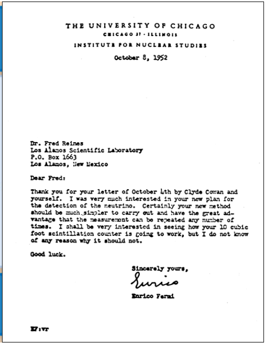


Fig. 1. The first conceptual proposed experiment to detect the free neutrino. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor as a neutrino source and the delayed coincidence reaction to reduce the background.

The Reines-Cowan experiment





THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

October 8, 1952

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

Good luck.

Sincerely yours,
Enrico
Enrico Fermi

EF:vr

- Neutrinos from nuclear reactor
- Problem: background from cosmic rays
- Solution: detect e^+ and n created by weak interactions
- Irrefutable proof that neutrinos exist in1956!

A better still nuclear reactor: the Sun!

- It is discovered that one Helium atom is slightly less massive than four Hydrogen atoms (ΔM)
- Eddington: nuclear reactions are responsible for energy production in the Sun ($E = \Delta M\, c^2$)
- Bethe proposes the sequence of reactions

$$p+p \to d+e^+ + \nu_e\,; \quad p+d \to {}^3\mathrm{He}+\gamma\,; \quad {}^3\mathrm{He}+{}^3\mathrm{He} \to {}^4\mathrm{He}+p+p$$

for the conversion $4\,p \to {}^4$He and the release of energy

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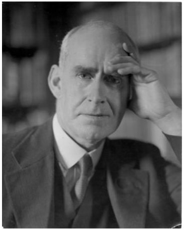

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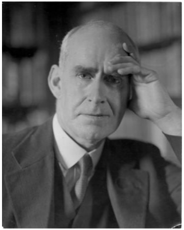

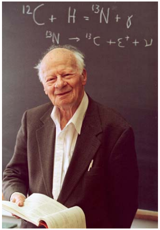

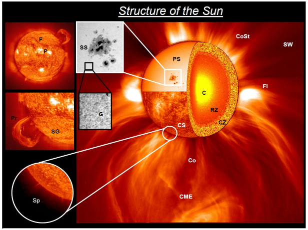

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The Sun as a source of neutrinos

- The previous sequence of reactions converts

$$4\,p + 2\,\mathrm{e}^- \longrightarrow {}^4\mathrm{He} + 2\,\nu_\mathrm{e} + (\gamma \text{ radiation})$$

and releases the energy

$$\begin{aligned} E_\gamma &= \left[4\,\mathrm{M}({}^1\mathrm{H}) + 2\,\mathrm{M_e} - \mathrm{M}({}^4\mathrm{He})\right] c^2 - 2\,\langle E_{\nu_\mathrm{e}} \rangle \\ &\simeq 26.7\ \mathrm{MeV}\ (4.3 \times 10^{-12}\ \mathrm{J}) \end{aligned}$$

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

$$N_{\nu_\mathrm{e}} \simeq 2\ \times L_\odot/(4.3 \times 10^{-12}\ \mathrm{J}) \simeq 1.8 \times 10^{38}\mathrm{s}^{-1}$$

- The neutrino flux on Earth due to pp weak fusion is

$$\phi(pp) \simeq N_{\nu_\mathrm{e}}/(4\,\pi D^2) \simeq 6.4 \times 10^{10}\ \mathrm{neutrinos}/(\mathrm{cm}^2\cdot\mathrm{s})$$

where $D = 1.5 \times 10^8$ km is the distance Earth-Sun

Detecting solar ν_e

- Davis sets up tank with 3.8×10^5 liters of C_2Cl_4 at a depth of 1.5 km in Homestake mine to detect $^{37}\mathrm{Ar}$ from

$$^{37}\mathrm{Cl} + \nu_e \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

  but ν_e's due to pp fusion have too low E_{ν_e} to activate it
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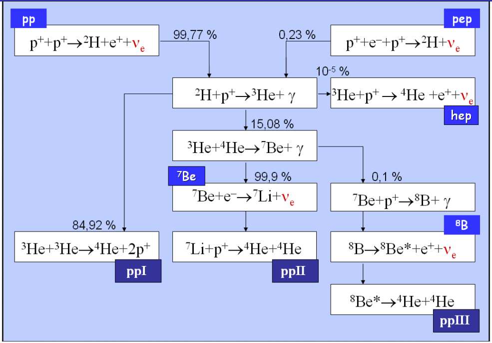

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Neutrino fluxes in pp chain

- Bahcall develops “standard solar model” (SSM) and estimates ν_e fluxes from reactions in pp chain
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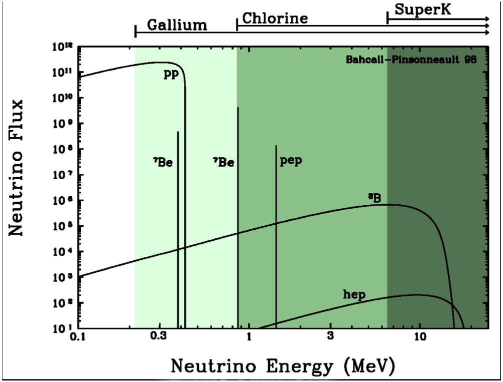

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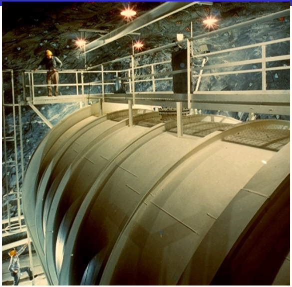
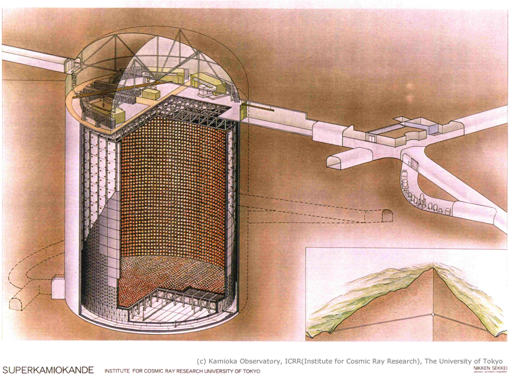
The solar neutrino problem



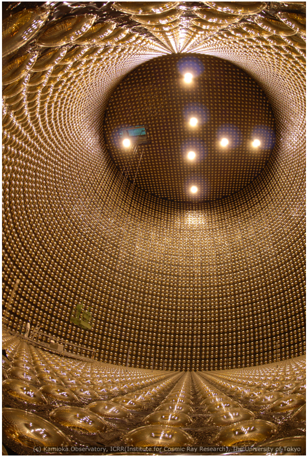
- Davis announces first results in 1968: only 1/3 of expected ν_e from SSM are detected
- Doubts on (i) Davis' ability to count a few ^{37}Ar atoms out of 10^{30} atoms in tank and (ii) validity of Bahcall's SSM
- Davis' first results were later confirmed over two decades of running!
- A different experiment (Kamiokande, 1989) confirms ν_e deficit observed by Davis

K and SK experiments in Japan



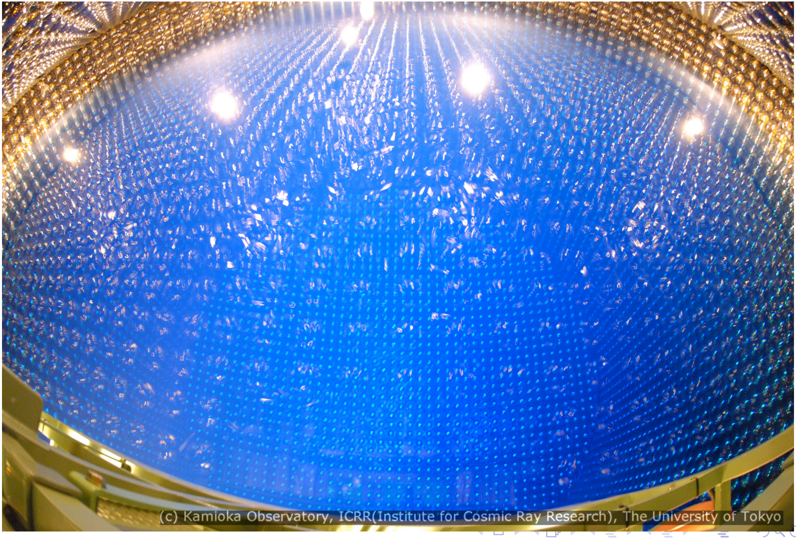
- In late 80's a new experiment, Kamiokande (K), comes online, later upgraded to Super-Kamiokande (SK)
- SK detector: ~ 50 ktons of pure water and $\sim 11,000$ photomultipliers (PMT's)

SK: a picture with installed PMT's

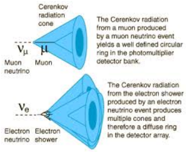


- Stainless steel cylindrical container (~ 39 m diameter and ~ 41 m height)

SK: a picture with nearly filled tank



K experiment confirms Davis' results



- A ν_{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 ν_{e} from direction and intensity of Cherenkov light
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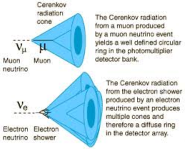

The New York Times

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

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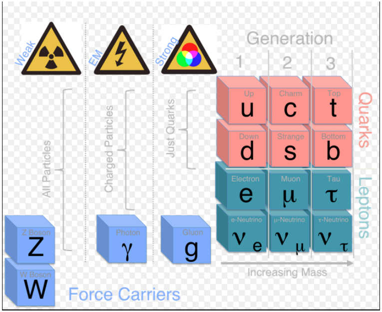
The Standard Model and neutrino flavors



- There are three neutrino flavors: $\nu_{\rm e}$, ν_μ, and ν_τ (and their three antiparticles: $\overline{\nu}_{\rm e}$, $\overline{\nu}_\mu$, and $\overline{\nu}_\tau$)

$$\mu^- \longrightarrow {\rm e}^- + \nu_\mu + \overline{\nu}_{\rm e} \qquad \tau_\mu \simeq 2.2 \times 10^{-6}{\rm s}$$

- ν_μ and ν_τ discovered, respectively, in 1962 and 2000

Solar neutrinos

Neutrino flavor oscillations I

- Pontecorvo's insight: neutrinos have mass and oscillate between flavors, for example $\nu_e \to \nu_\mu$ or $\nu_e \to \nu_\tau$
- Only ν_e's are produced by the Sun and can be detected in Davis' experiment, while ν_μ and ν_τ escape detection
- How do oscillations occur? In Quantum Mechanics (QM) particles can also be described by waves

$$\lambda = h/p \qquad h = \text{Planck constant} \qquad p = m\,v \text{ momentum}$$

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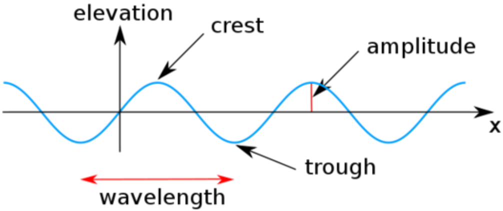
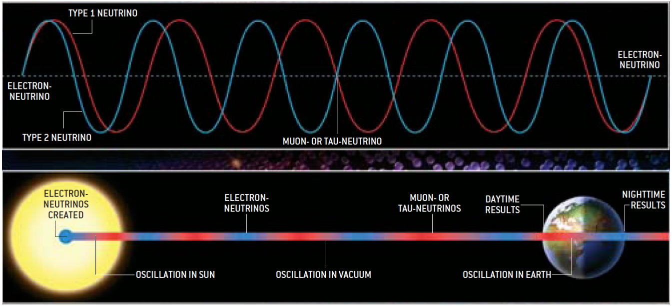


Neutrino flavor oscillations II



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

$$P_{\nu_e \to \nu_\mu}(x) = \sin^2(2\,\theta)\,\sin^2\left(\frac{\pi\,x}{L}\right) \quad \text{with } L = \frac{2\,h}{c^3}\,\frac{E}{m_2^2 - m_1^2}$$

- Presence of matter (electrons in solar interior) modifies $P_{\nu_e \to \nu_\mu}(x)$ and enhances oscillations (MSW effect)

Towards the solution: SK and atmospheric ν_μ

- Evidence accumulates that neutrinos oscillate: SK measures ν_e's and ν_μ's due to cosmic rays

$$(\#\nu_\mu)/(\#\nu_e) \simeq 1 \text{ versus expected} \simeq 2$$

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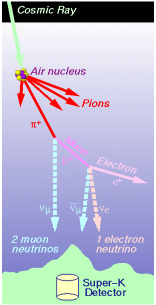

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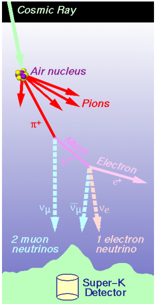

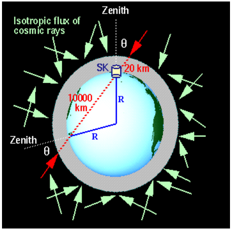

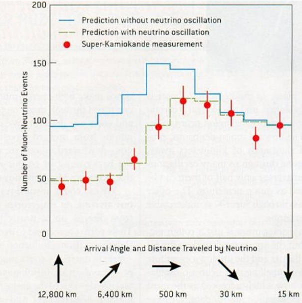

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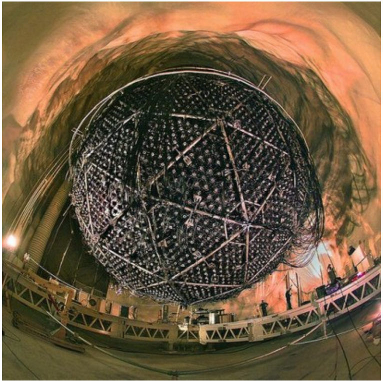
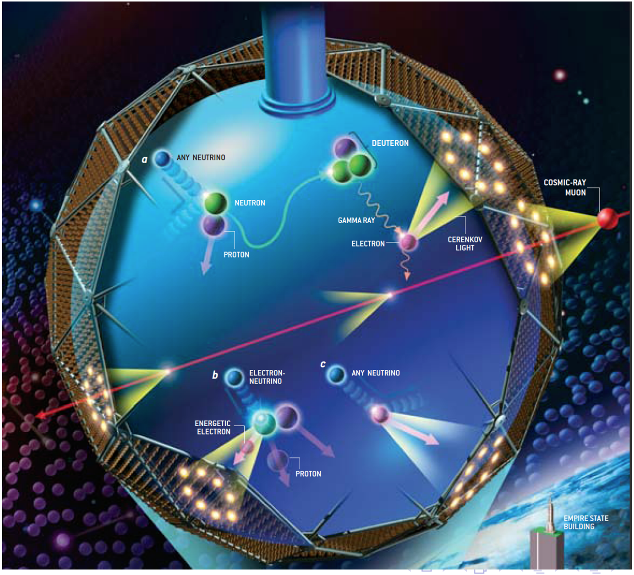
The Sudbury Neutrino Observatory (SNO)



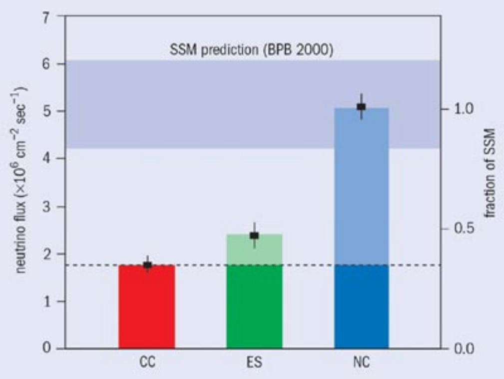
- 1,000 tons of heavy water ($\mathrm{D_2O}$) and 9,600 PMT's mounted on a geodesic support structure
- SNO detects neutrinos via the processes:

$$d + \nu_{\mathrm{e}} \longrightarrow p + p + \mathrm{e}^- \qquad d + \nu_x \longrightarrow p + n + \nu_x$$

The SNO experiment



The SNO results: the solar ν_e problem solved!



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

Summary

- The solar neutrino problem: the story of a triumph!
- The physics of neutrinos is now a field of intense research activity:
  - determination of Δm^2_{ij} and θ_{ij}
  - role of neutrinos in supernova explosions
  - neutrinos and the matter-antimatter asymmetry problem
  - $\cdots$
- The support of the U.S. Department of Energy under contract DE-AC05-06OR231 is gratefully acknowledged

ν squared-mass splitting and mixing angle