Neutrinos: Past, present and future

Summer student intro talk

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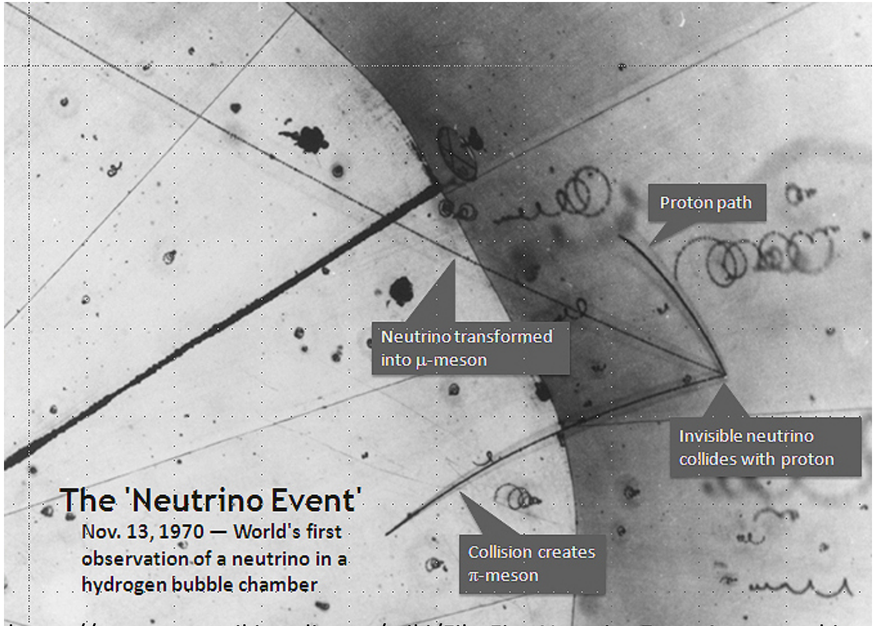


https://commons.wikimedia.org/wiki/File:FirstNeutrinoEventAnnotated.jpg

Outline

- History of neutrinos
- Neutrinos in the Standard Model
- The Solar Neutrino Problem
- Neutrino oscillations
- Open questions and current experiments

Beta decay

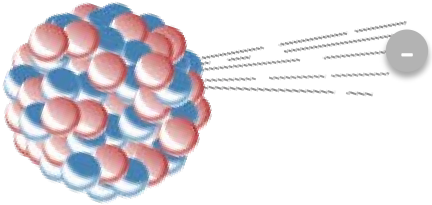
- Measurements of β rays (electrons) showed a continuous energy spectrum (1911)
- Hypothesis:

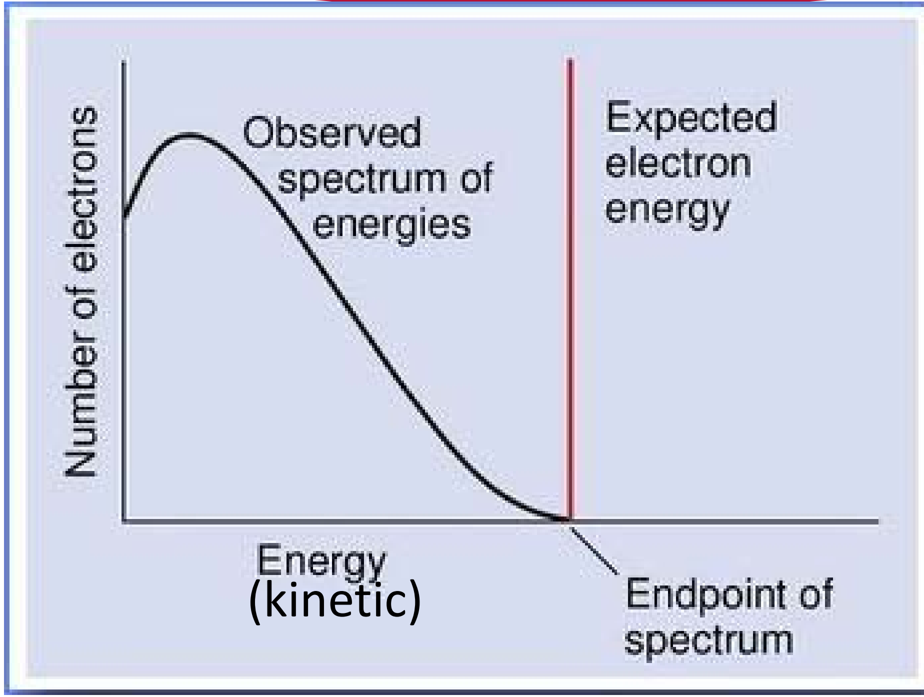
(neutral particle) → (positive particle) + (β ray)

Or in modern language:

$$n \rightarrow p + e^-$$

However, in a 2-body decay, the decay products can only have a specific energy and momentum, *if energy is conserved*





Dear radioactive ladies and gentlemen (1930)

Dear Radioactive Ladies and Gentlemen,
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, ***I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy****.* ***Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons****, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*

I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think about this at all, like new taxes"*. From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.*

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December*. With my best regards to you, and also to Mr Back.*
Your humble servant,

W. Pauli

Timeline

- 1900: Becquerel measures m/e for β rays and finds the same value as Thomson's "cathode rays" → identified as the same particle, the electron
- 1911: Lise Meitner and Otto Hahn see hints that beta decay spectrum is continuous, confirmed in 1914 by Chadwick
- 1930: Pauli proposes an undetectable "neutron" to save conservation of energy

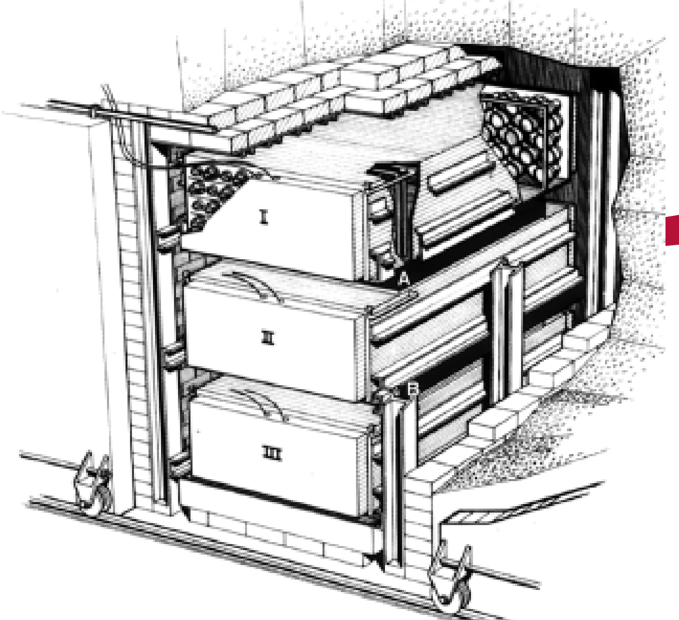
$$n \rightarrow p + e^{-} + \nu$$

- 1932: Chadwick discovers "neutron"
- 1934: Fermi at seminar on his new theory of beta decay, asked whether the neutral particle in the decay is Chadwick's neutron, he says no, it's a smaller one, a little neutron, "neutrino"
- Need a strong source of neutrinos to detect them!

Lise Meitner, first female physics professor in Germany, fled in 1938 to Sweden.

Excluded from 1944 Nobel Prize (awarded to Otto Hahn alone for discovery of fission)

First detection of neutrinos (1956)



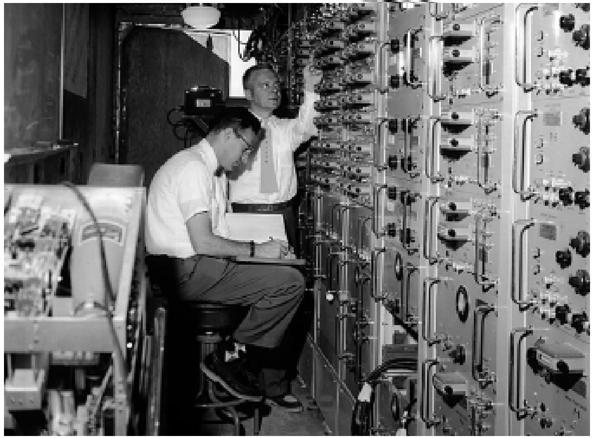
- Understood that nuclear reactors produce large amounts of (anti) neutrinos
- Experiment by Reines and Cowan at Savannah nuclear power plant
- Clever use of "inverse beta-decay" reaction to efficiently detect neutrino events:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Since water contains a lot of "free-ish" protons (nuclei of H), it is a good target for the reaction.

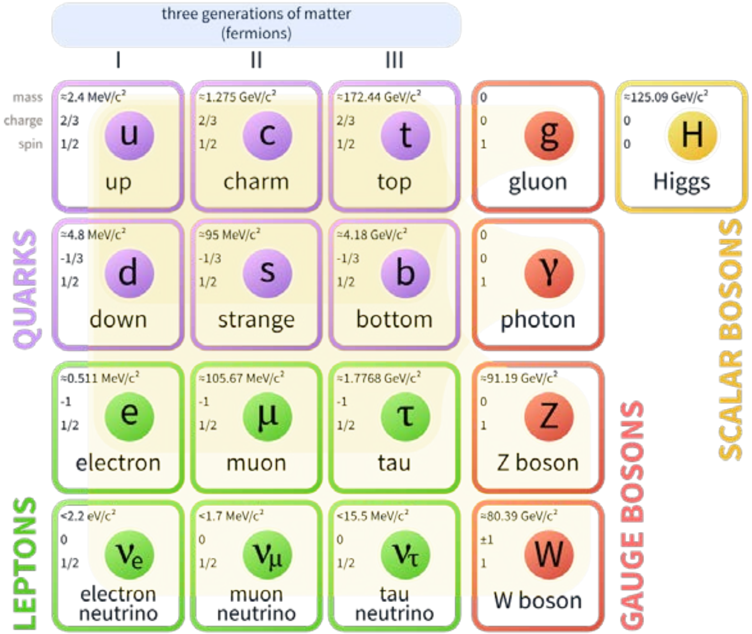
Detection by "triple coincidence":

- "Prompt" 2x 511 keV annihilation gamma rays from positron (back to back)
- "Delayed" (5μs) neutron capture on cadmium (seen as 2-3 gammas summing to ~9MeV)



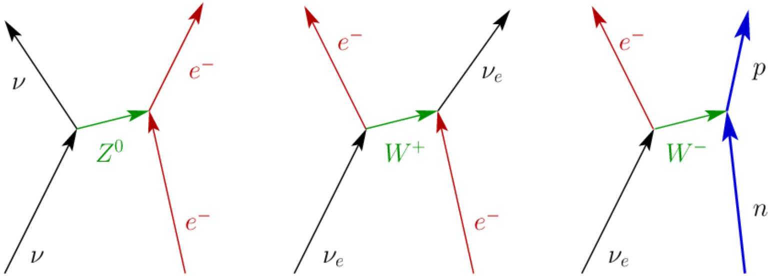
Neutrinos in the standard model

Standard Model of Elementary Particles



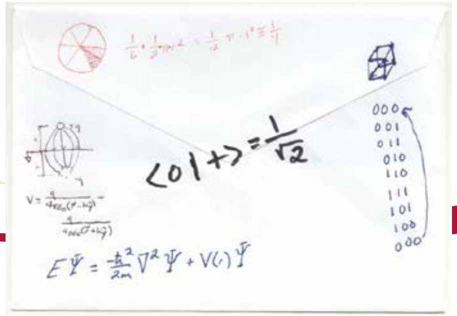
- 3 flavours of neutrinos
- Interact (created) only through the Weak interaction
- Neutrinos are only left-handed (anti neutrinos right-handed) because of the Weak interaction

→ Neutrinos must be massless



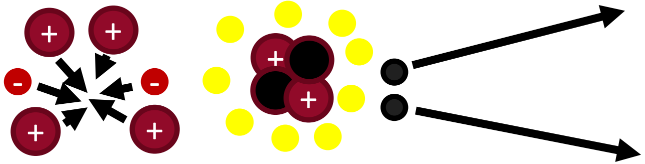
Neutral current   Charged current

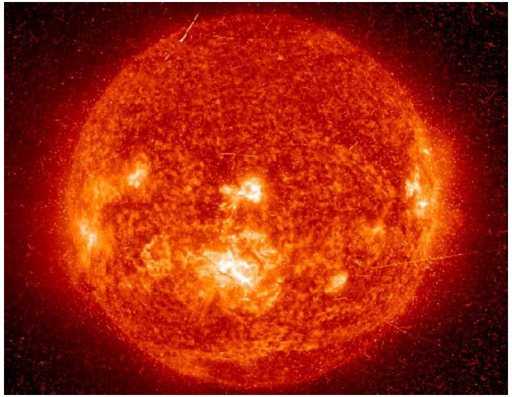
Energy production in the Sun (Phys 242)



- Main mechanism of energy production in the Sun is fusion (H → He):

$$4\,p + 2\,e \rightarrow \alpha + 2\,\nu \text{ (+ energy)}$$





- Stuff on the left is heavier than stuff on the right:

(1eV = 1.6×10^{-19}J)

m_p=938.3 MeV/c^2, m_e=511 keV/c^2, m_α=3727.5 MeV/c^2, m_ν~ 0

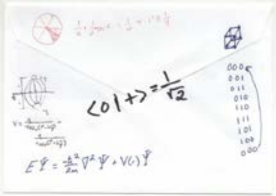
LHS: 3754.2 MeV/c^2 **RHS=3727.5 MeV/c^2**

- Excess energy = c^2x(3754.2-3727.5) = **26.7 MeV**
- Based on the brightness of the Sun, astrophysicists can estimate the rate at which it produces energy (the "luminosity"):

L=3.9 x 10^{26} J/s= 24.4x10^{39} MeV/s

→We can estimate how many reaction per second occur in the Sun, and we can hope to verify that by measuring (on Earth) the flux of neutrinos emitted by the Sun

Rate of solar neutrino production



- Rate of fusion reactions in the Sun:

$$\Gamma_{\odot} = \frac{L}{\Delta E} = 9.1 \times 10^{37} s^{-1}$$

- Rate of neutrinos produced in the Sun:

$$\Gamma_{\nu} = 2\Gamma_{\odot} = 18.2 \times 10^{37} s^{-1}$$

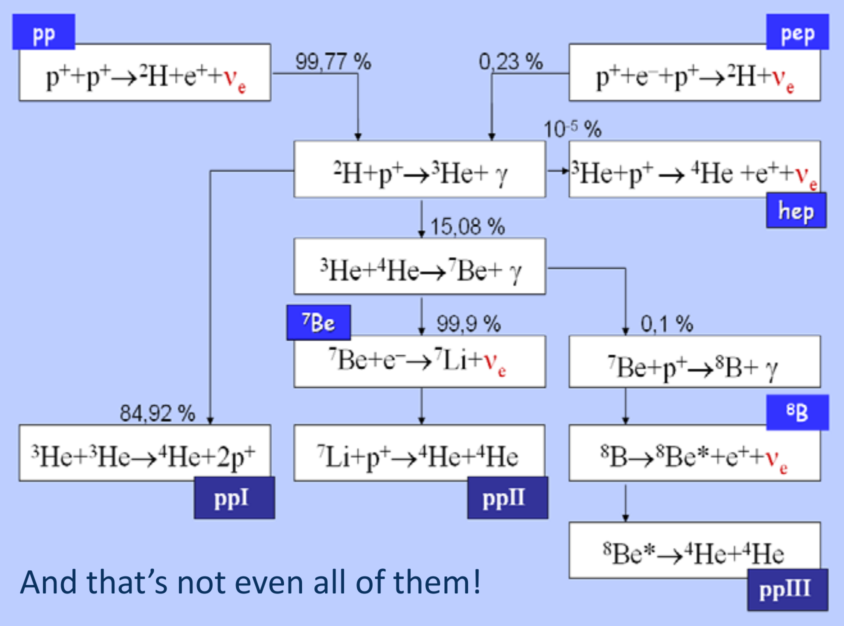
- Rate of neutrinos on Earth:

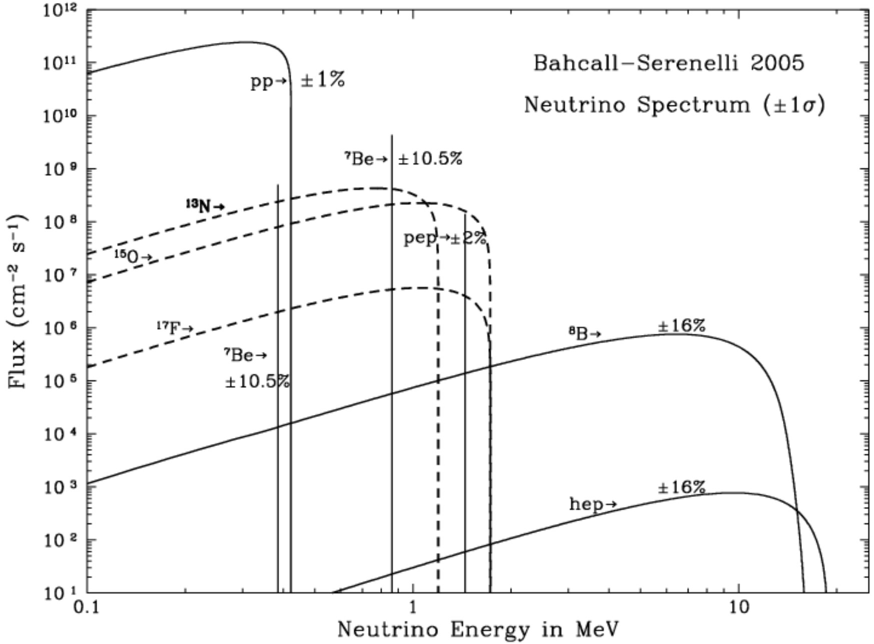
$$\Gamma_{\nu}^{\otimes} = \frac{\Gamma_{\nu}}{4\pi D^2} = 6.4 \times 10^{14} m^{-2} s^{-1} = 6.4 \times 10^{10} cm^{-2} s^{-1}$$

- That's a lot of neutrinos…

John Bahcall, first to calculate in the early 1960s

Actual fusion reactions in the Sun





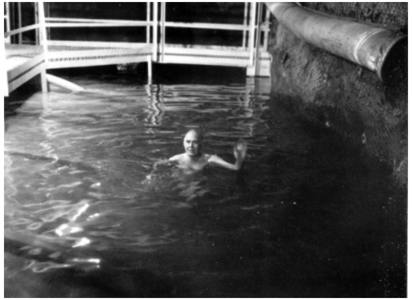
In an experiment, you have to factor in the fact that there are neutrinos from many different reactions, with a wide range of kinetic energies, and that only the most energetic ones stand a chance of being detected. A difficult calculation to make an accurate prediction!

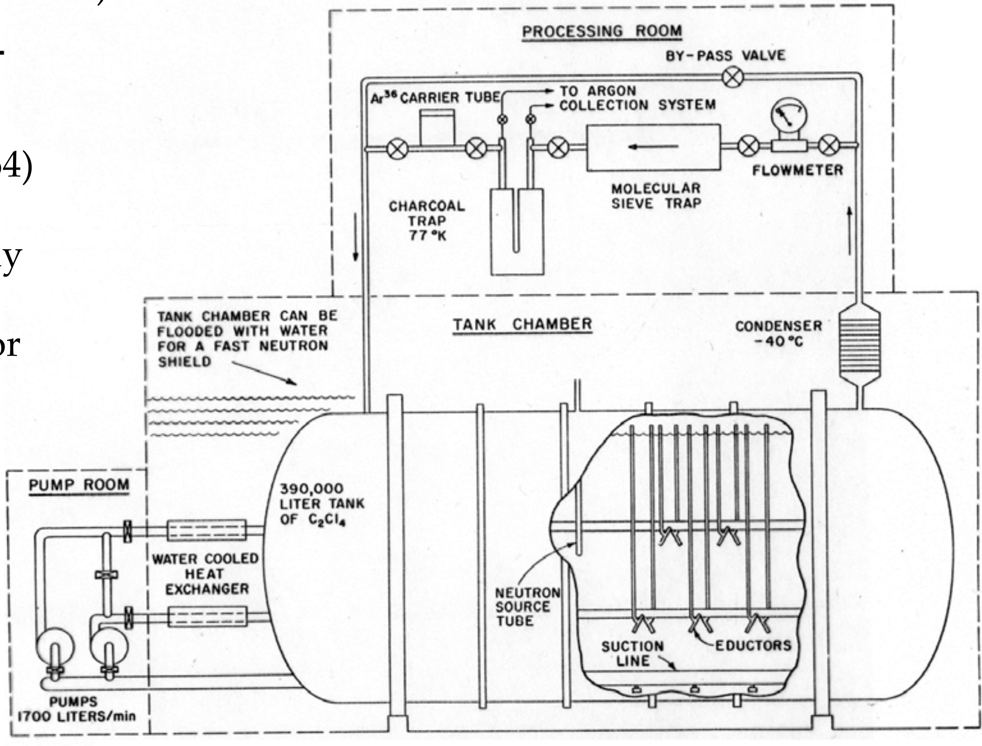
Detecting solar neutrinos

Detecting electron flavour neutrinos using 400,000 liters of C_2Cl_4 through "inverse beta decay" with an 0.8 MeV threshold (mostly ^{8}B neutrinos):

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

- Proposed by John Bahcall and Ray Davis (PRL **12**, 1964)
- Experiment was located in Homestake mine, South Dakota, 4,850ft underground to shield from cosmic ray muons that can also make ^{37}Ar
- About 15 argon atoms extracted every few months (for 10^{30} chlorine atoms) !!!





From: http://bnl.gov

Results from Davis experiment, and the solar neutrino problem

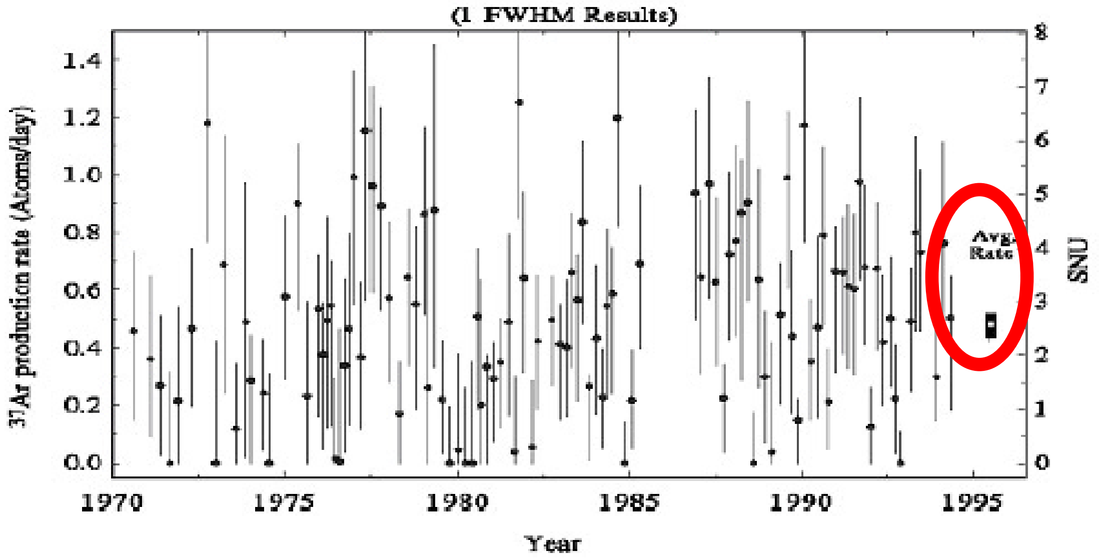


Fig. 2 Final results of Davis experiment (Cleveland et al. 1998). The average rate of about 2.5 SNU is much lower than the calculated rate of about 8.6.

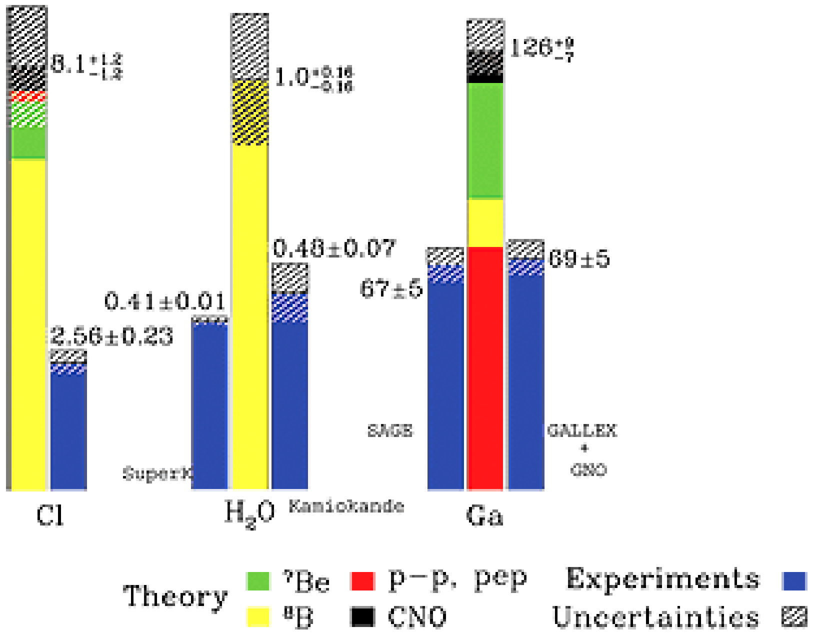
Note the time scale; 25 years of data!

Observe **2.5 SNU instead of 8.6 SNU**, what gives?

- It's crazy to think you could do a reliable experiment counting single atoms, the results are obviously wrong
- It's crazy to think you can model the Sun this precisely, the model is obviously wrong

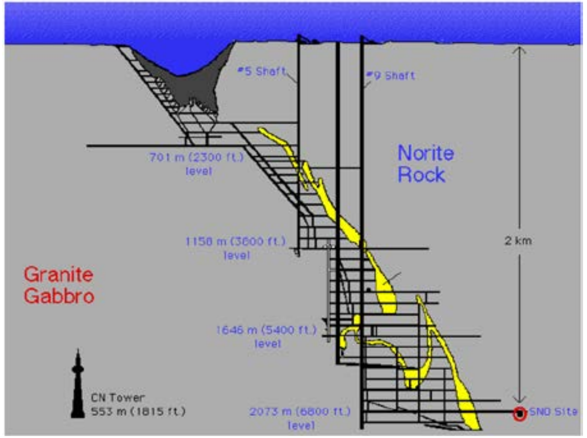
The Solar Neutrino Problem(s)

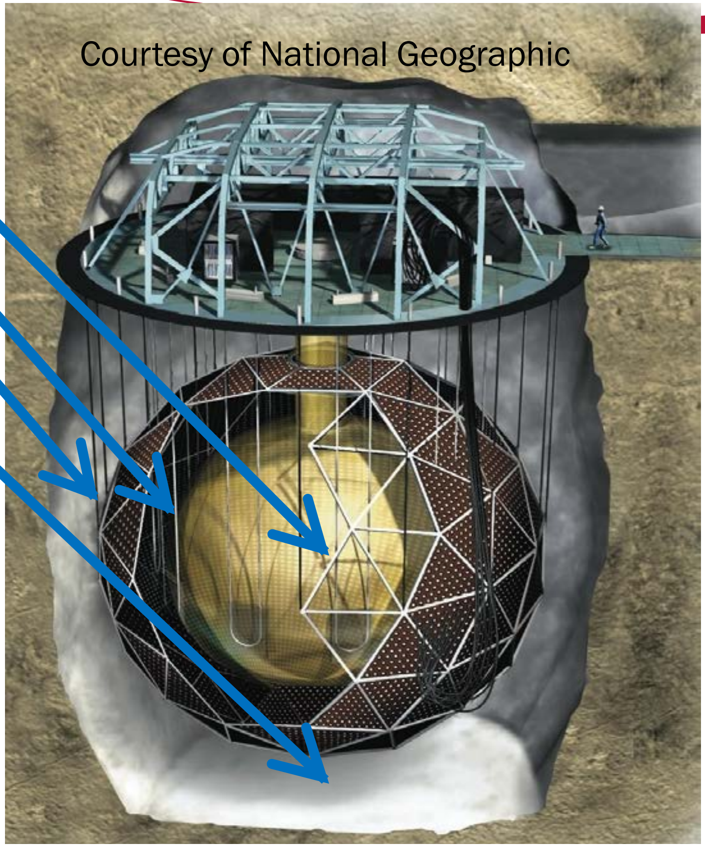
- Other experiments using Gallium, Chlorine, Water, confirm the discrepancy with the solar model predictions
- After 30 years, people were starting to really worry about what is going on
- Herb Chen proposed an experiment using **heavy water** that could test whether the issue is with neutrinos, instead of the theory or the experiments.



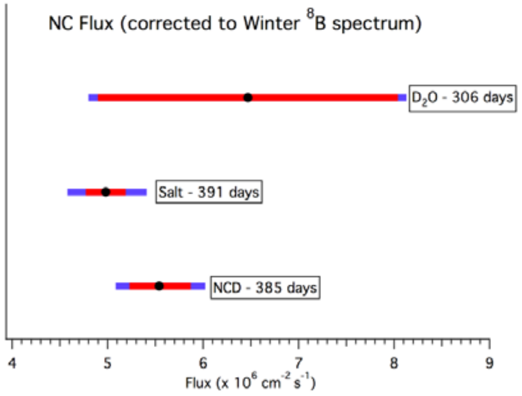
The Sudbury Neutrino Observatory

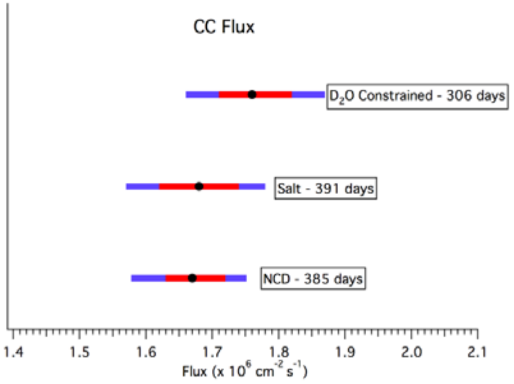
- 1000 tonnes Heavy Water (D_2O) Cherenkov detector
- 12m diameter Acrylic Vessel (AV)
- ~9500 PMTs on 18m diameter geodesic structure (PSUP)
- Surrounded by 7000 tonnes of ultra-pure light water to shield from rock

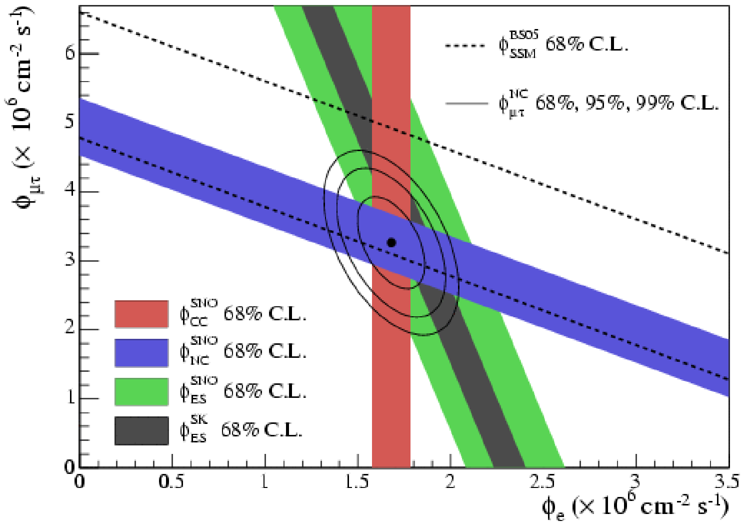




Results







- 3 phases provided consistent results
- The total flux (as measured by NC) exactly matches the model
- The electron flavour flux (as measured by CC) exactly matches what the other experiments saw
- Davis and Bahcall both correct!
- **Neutrinos change flavour on their way from the Sun**

Neutrino oscillations

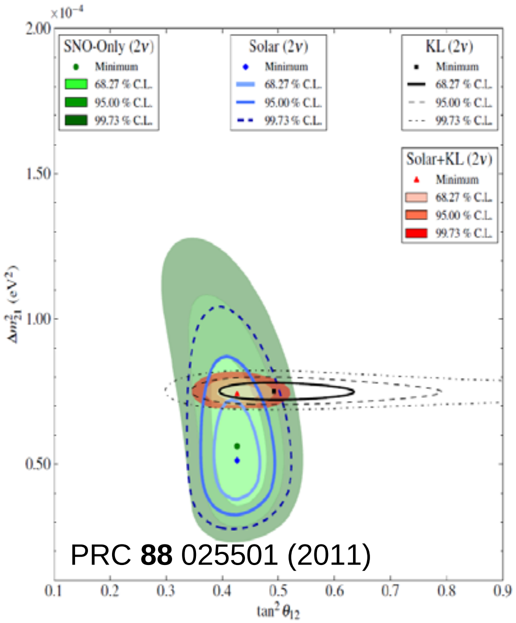
- Neutrinos exists as "superpositions" of different states (flavours) until they are measured. Exactly like Schroedinger's cat.

- The probability of being in a given flavour oscillates with time (neutrino oscillations in vacuum):

$$P_{\nu_e \to \nu_e} = 1 - \frac{1}{2}\sin^2(2\theta_{12})\left(1 - \cos\left(\frac{\Delta m_{21}^2}{2c\hbar}\frac{L}{E}\right)\right)$$

- The frequency is non zero only if neutrinos have mass!
- The Standard Model is wrong!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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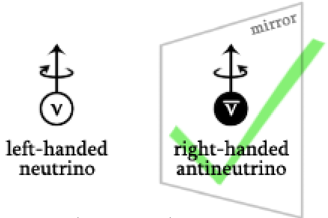
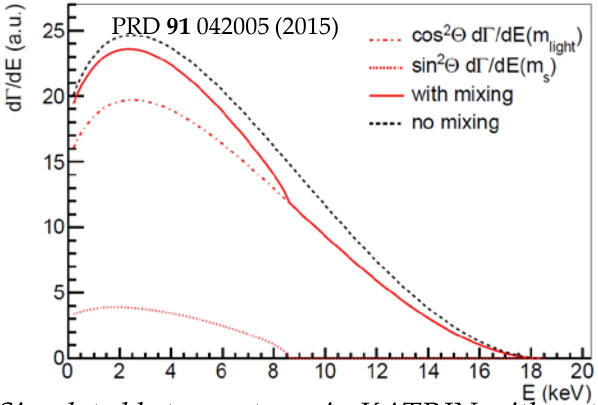
What we don’t know about neutrinos

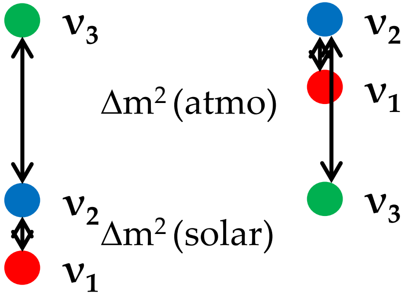


Does the Weak interaction only make left-handed neutrinos?



Simulated beta spectrum in KATRIN with a sterile neutrino component

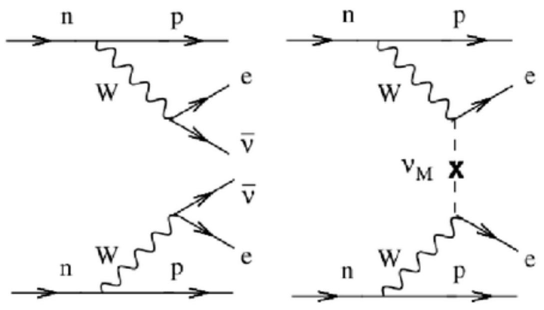
- What are the neutrino masses?
- What is the mass hierarchy?
- What kind of mass do they have (Majorana or Dirac)?
- Do neutrinos violate CP?
- Are there additional types that don’t interact through the Weak Interaction (“steriles”)?

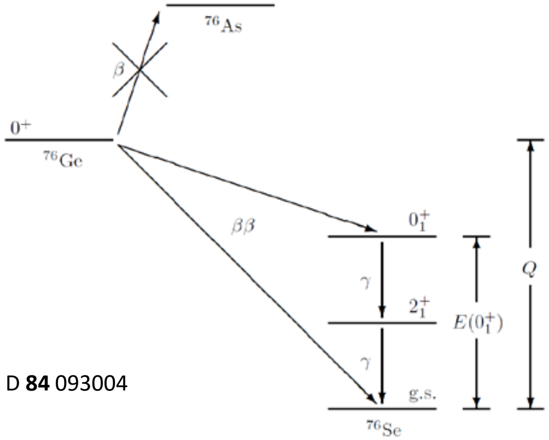


Normal and inverted hierarchies

(Neutrinoless) double beta decay

- Beta decay is forbidden in certain isotopes, while double beta decay is allowed
- If neutrinos are Majorana, a fraction of those decays may be "neutrinoless"
- This is the only practical way to show that neutrinos are Majorana
- Experimental signature is a peak at the end of the energy spectrum of the emitted electrons





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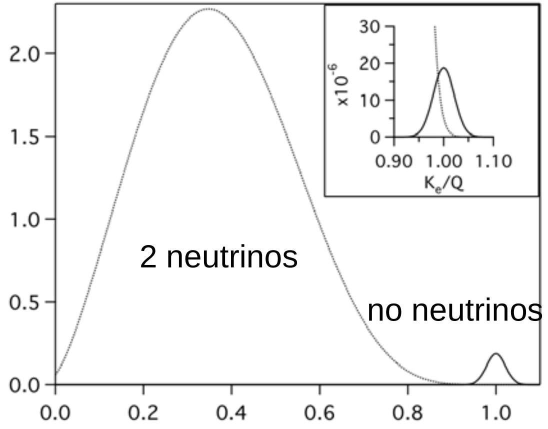


Experimental searches for neutrinoless double beta decay

- Perform a "counting experiment":
  - *If no counts are seen, the half-life is at least as long as…*

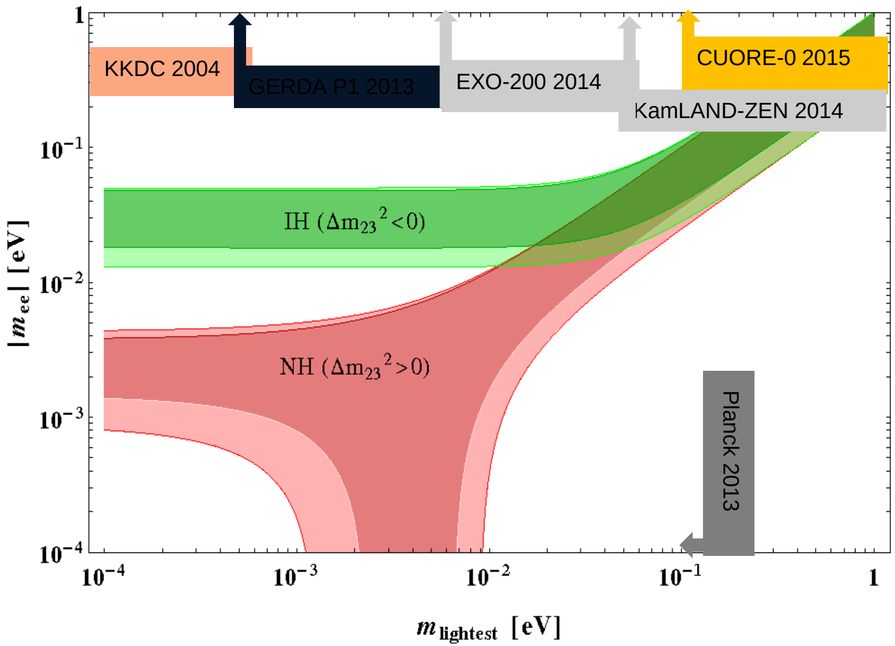
$$T_{1/2}^{0\nu} = \left(G_{0\nu} |M_{0\nu}|^2 \left(\frac{m_{ee}}{m_e} \right)^2 \right)^{-1}$$

$$m_{ee} \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

Sensitivity:

$$T_{1/2}^{0\nu} \propto a\epsilon \sqrt{\frac{Mt}{\sigma_E B}}$$

abundance (a), Detect eff. (ϵ), mass (M), live-time (t), energy resolution (σ_E), background rate (B)



Other news in neutrino physics

- Observation of coherent neutrino-nucleus scattering
- Measuring neutrino mass (in the lab)
- Measuring the sum of neutrino masses (cosmology)
- Measuring the mass hierarchy
- Measuring the CP violating phase
- Looking for sterile neutrinos