Solar neutrinos

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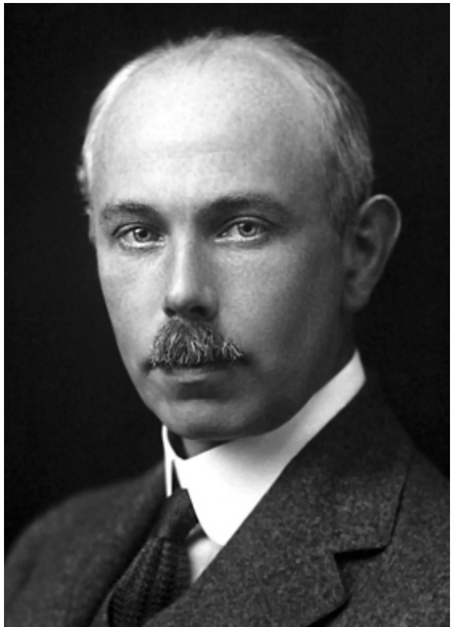
A journey to the Sun

- F. W. Aston discovered that a He atom has a mass defect to four H atoms of 1 part in 120

- A. Eddington proposed (1920) that the Sun produces heat and light by means of a nuclear transformation of H into He



The CNO cycle

- H. Bethe proposed a cycle of nuclear transformation for carbon-containing stars (CNO cycle)

$$ {}^{12}_{6}C + p \rightarrow {}^{13}_{7}N + \gamma $$

$$ {}^{13}_{7}N \rightarrow {}^{13}_{6}C + e^{+} + \nu $$

$$ {}^{13}_{6}C + p \rightarrow {}^{14}_{7}N + \gamma $$

$$ {}^{14}_{7}N + p \rightarrow {}^{15}_{8}O + \gamma $$

$$ {}^{15}_{8}O \rightarrow {}^{15}_{7}N + e^{+} + \nu $$

$$ {}^{15}_{7}N + p \rightarrow {}^{4}_{2}He + {}^{12}_{6}C $$

- globally

$$ {}^{12}_{6}C + 4p \rightarrow {}^{12}_{6}C + {}^{4}_{2}He + \boxed{2e^{+} + 3\gamma + 2\nu} $$

energy

Sun-like stars

- The CNO cycle, works only if the star contains carbon and its *T* > 20 millions K
- In the Sun carbon is rare and *T* ~ 15 millions K ➔ a different process is necessary
- Bethe found a solution (1939):
  - for Sun-like stars, H atoms are decomposed into protons and electrons
  - when two protons collide, the nuclear fusion of the two is possible

The *pp* chain

$$p + p \rightarrow d + e^{+} + \nu$$

$$d + p \rightarrow {}^{3}He + \gamma$$

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$$

- Globally

$$4p \rightarrow {}^{4}He + \boxed{2e^{+} + 2\gamma + 2\nu}$$

energy

- Positrons annihilate with electrons producing gamma rays
- All gamma rays bounce repeatedly with charged particles, losing energy in their way towards the surface
- At last they emerge from the star as light (from IR to UV) after thousands of centuries

Solar neutrinos

- The neutrinos, instead, would traverse the Sun unimpeded and reach the Earth in about eigth minutes
- Bethe’s theory explained the facts and predicted the production of neutrinos
- But in 1939 the neutrino was still considered just a theoretical construction

- This changed after Pontecorvo’s 1946 paper and Cowan and Reines’ 1956 antineutrino discovery
- The possibility to verify Bethe’s theory, searching for solar neutrinos was considered

Another ‘failure’ of Davis’

- If solar neutrinos were produced in the CNO cycle, Davis’ apparatus could detect them
- But Davis’ try failed so
  - either the idea of solar neutrinos was wrong
  - or the CNO cycle was not important to the Sun

- Actually in the Sun the dominant process is the *pp* chain whose neutrinos have insufficient energy (less than one half) for the Cl reaction (860 keV) in Davis’ experiment to happen

Good news...

- In the *pp* chain one He^4 nucleus is produced
- He^4 has kept accumulating in the Sun for 5 billions years
- ➔it is possible that

$$^{3}He+{}^{4}He \rightarrow {}^{7}Be+\gamma$$

- In 1959 two nuclear physicists* found that berillium-7 production was 1,000 times more probable than expected
- ${}^{7}Be$, on its turn, can fuse with a proton, producing boron-8

$$^{7}Be+p \rightarrow {}^{8}B+\gamma$$

- ${}^{8}B$ decays generating a neutrino with an energy of 14 MeV

$$^{8}B \rightarrow {}^{8}Be+e^{+}+\nu$$

- and this energy is well over the Cl threshold of Davis' experiment

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* H. D. Holmgren and R. L. Johnston

... and bad news

- This encouraged Davis and Calvin to start a new experiment (1959), with the Savannah River detector
- To reduce the cosmic-ray background, the experiment moved in a mine 700 meters underground

- Unfortunately nuclear physics experiments found that the probability for Be^7-p fusion was very small
- and Davis again could not find any convincing evidence of solar neutrinos

Bahcall & Davis

- J. Bahcall: the probability of weak interactions in the stars must be higher than in the lab on Earth
- He computed the probability of the Be^7-p fusion: the result (1963) was not encouraging
- The probability in the Sun was higher than on Earth, but a 4000-liter detector would capture one neutrino in 100 days
- ➔Davis thought of a detector 100 times bigger
- To suppress the cosmic-ray backgound, they decided the experiment had to be moved 1500 meters underground

Good news again

- B. Mottelson noticed that solar neutrinos should have enough energy to form the Ar nucleus in an excited state...
- So Bahcall computed the new process, finding that neutrino capture by excited Cl increased 20 times

Homestake, 1966

- The new experiment was built in the Homestake gold mine in Lead, SD
- The tank contained 615 tons of C_2Cl_4 , a normal cleaning agent

- By September 1966 it was ready to start making the history of physics

How many solar neutrinos?

- On the basis of the Standard Solar Model (SSM), Bahcall calculated the solar neutrinos flux on Earth, finding a total of 66×10^{9} s^{-1} cm^{-2}

- Unfortunately most of the times the neutrinos have insufficient energy to react with Cl

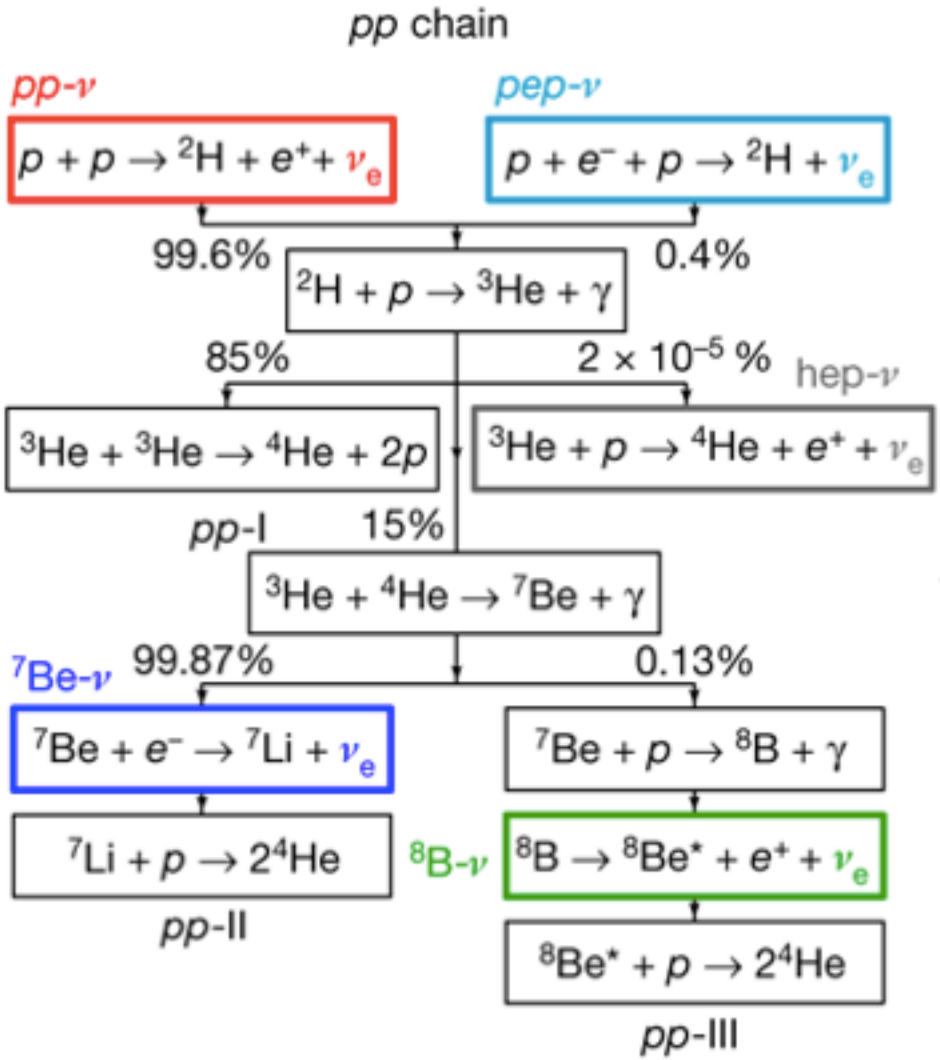
- Moreover nearly all of them would pass through the detector without interaction

The SNU

- Bahcall expressed the probability that a solar neutrino interacts with a Cl nucleus introducing the Solar Neutrino Unit:

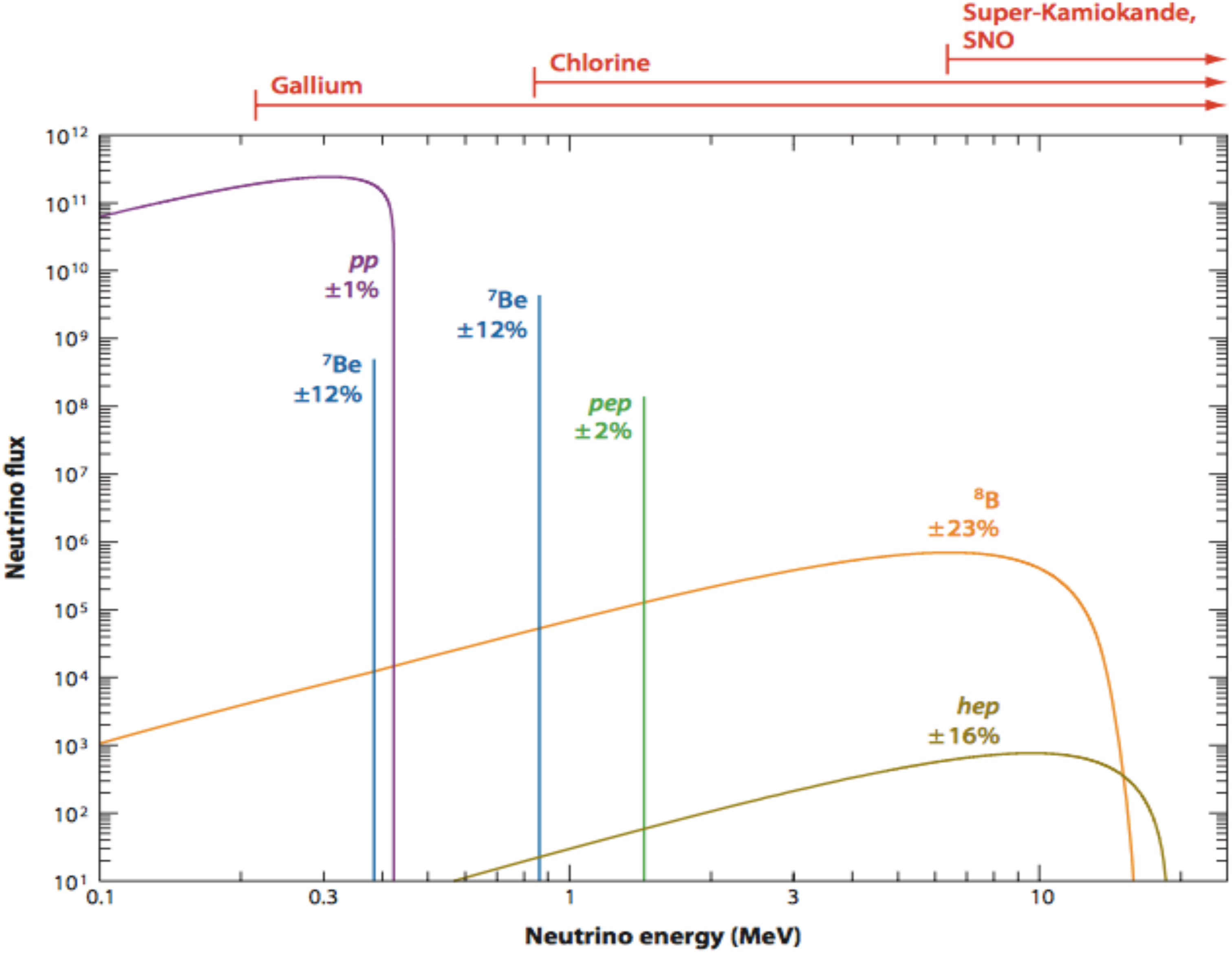
  1 SNU=10^{-36} reactions/nucleus/s
- In 400,000 liters of detergent there are about 2 x 10^{30} Cl nuclei ➔the mean neutrino capture time is 6 days per SNU
- Bahcall's result was 7.5+-3 SNU and about 6 of these were produced by B^8, the ones which Davis' experiment was able to detect
- Expected detection: 1 neutrino per day

pp chain neutrinos *



* Nature **562**, 505-510 (2018)

Solar neutrino spectrum



Calculated energy spectrum of the solar neutrinos according to the Standard Solar Model

Neutrinos eventually!

(but too few)

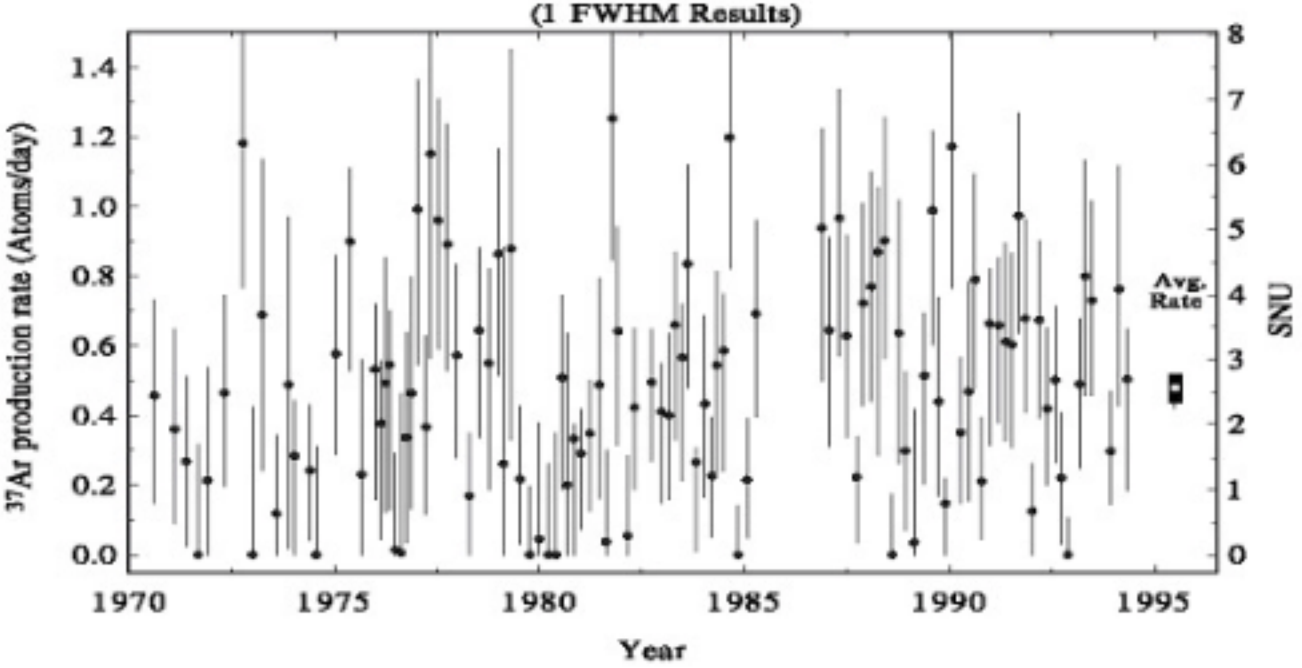
- 1968: first results published: the production frequency of neutrinos was too small, 3 SNU at best
- In the following years the cosmic-ray background was reduced, the SSM reexamined, while the statistics was slowly accumulating... but neutrinos kept missing

➔ Solar neutrino problem

Davis' experiment results*

- Davis' experiment ran continuously until 1994
- 1998: final results:
  - 2200 Ar atoms produced,1997 extracted
  - 875 counted in the PC: 109 BG events, 776 produced by solar neutrinos

Production rate:
2.56
± 0.16 (stat.)
± 0.16 (syst.) SNU



* The 2002 Nobel Prize in Physics - Advanced Information". Nobelprize.org. Nobel Media AB 2014. Web. 10 Jul 2018. <http://www.nobelprize.org/nobel_prizes/physics/laureates/2002/advanced.html>

The ignored solution

- In 1968, when Davis' first results appeared, Pontecorvo and Gribov proposed the right solution to the missing neutrinos
- The idea of neutrino oscillations had been first proposed by Pontecorvo (1957) as neutrino-antineutrino transitions
- This was later developed to the theory of neutrino flavor oscillation, by Maki, Nakagawa and Sakata (1962) and Pontecorvo (1967)
- The theory is based on the existence of two neutrino states
- Quantum mechanics allows neutrinos to oscillate between the two states, provided they have mass
- The idea that neutrinos have mass, went against the Standard Model of the elementary particles and for this reason the idea was simply ignored

The solar neutrino problem

- 1978: at the Brookhaven conference it was realized that a new experiment was necessary to detect the neutrinos from the dominant *pp* fusion

- From 1968 to 1988 Davis' experiment was the only active experiment investigating solar neutrinos

Neutrinos from the *pp* process

- Gallium provides the only feasable means to measure the low-energy *pp* neutrinos
- Thanks to a threshold of only 0.233 MeV for the reaction

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

  with a neutron in the Ga nucleus
- The detection frequency of this detector would be 132 SNU, compared to the 7,5 SNU of Davis' detector

All the gallium in the world

- Two experiments were built:
  - GALLEX under the Gran Sasso, Italy
  - SAGE under the Caucasus mountains, former USSR
- Both experiments used the germanium-producing reaction

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

- To build SAGE all the world supply of Ga was necessary
- GALLEX had to wait two more years for the production of the Ga it needed

Why two experiments?

- Both experiments used the same reaction
- The composition of the Ga target was metallic gallium for SAGE and a liquid gallium chloride solution for GALLEX
- The different forms of the gallium are susceptible to very different types of backgrounds, and thus the two experiments provided a check for each other

SAGE (1989-2010)

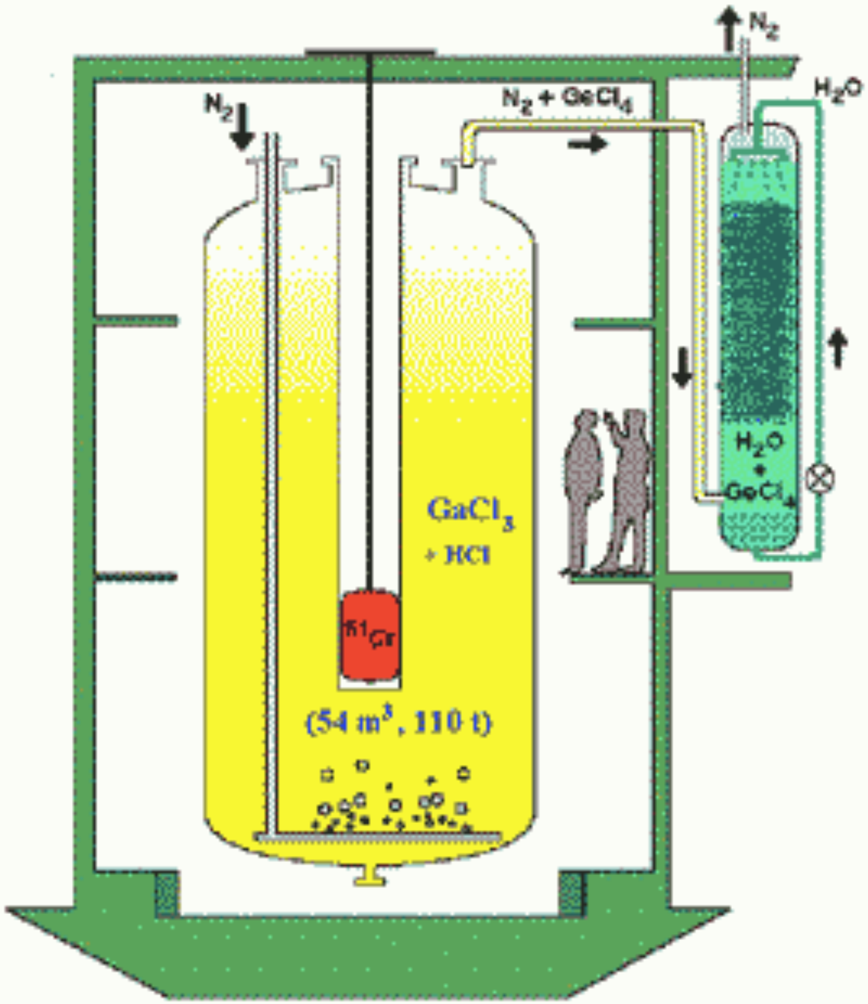
- The target was 57 tonnes of liquid Ga metal
- Once a month Ge was chemically extracted from the Ga
- ^{71}Ge undergoes electron capture ($T_{1/2}$ = 11.43 days)

$$e^- + {}^{71}Ge \rightarrow \nu_e + {}^{71}Ga^*$$

- The extracted amount of Ge can be determined with a proportional counter by measuring the activity of the resulting Ga atom in an excited state
- The excess energy is carried off by low-energy Auger electrons and by X-rays, which, taken together, make for a characteristic decay signature

GALLEX* (1991-1997)

- GALLEX 54-m^3 detector tank was filled with 101 tons of a solution of $GaCl_3$ and HCl, for a total of 30.3 tons of Ga
- The produced Ge was chemically extracted and detected by counters



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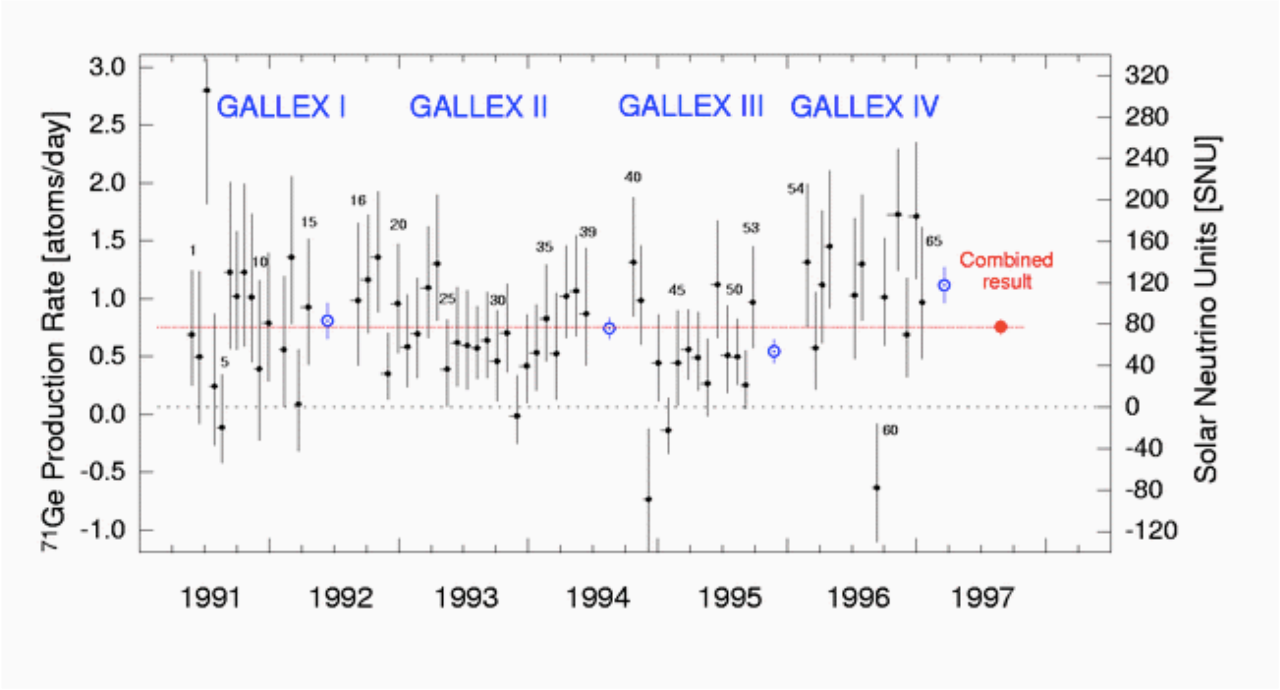
* https://www.mpi-hd.mpg.de/lin/research_history.de.html#gallex

Results



- The SSM predicted 130 SNU
- SAGE’s result was 65.4 SNU (based on the 1990-2007 data)
- GALLEX measured a rate of 77.5 SNU
- Both experiments found about half as many neutrinos as expected

KamiokaNDE (1983)

- The detector was a tank 16.0 m in height and 15.6 m in width, containing 3,048 tonnes of ultra-pure water and about 1,000 PMTs
- The aim of the experiment was to find whether the proton decays
- Since neutrinos are a major background to the search for proton decay, the study of neutrinos became a major effort
- Kamiokande could detect neutrinos in real time, with an obvious advantage on chlorine and gallium detectors...
- where neutrinos were counted one month after interaction and radiochemical extraction of the produced Ar or Ge atoms

KamiokaNDE II

- The detector was upgraded, starting in 1985 to allow it to observe solar neutrinos via elastic scattering (active for the three neutrino flavors with different sensitivities)

$$\nu_k + e^- \rightarrow \nu_k + e^-$$

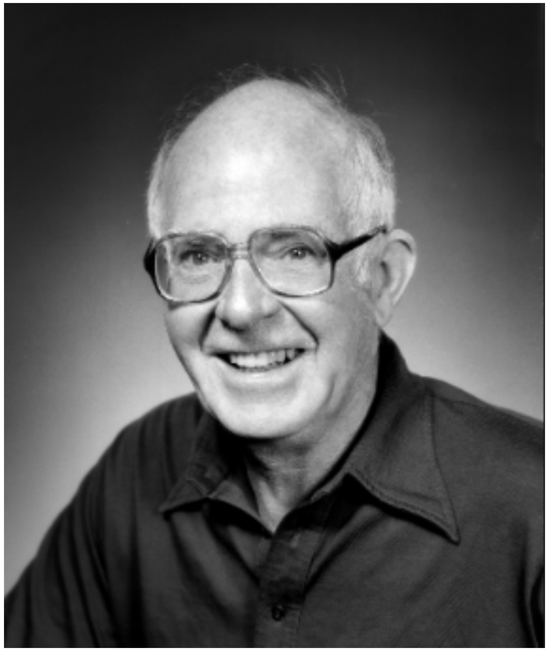
- 1988: K-II observes solar neutrinos produced by B^8
- The ability of the experiment to observe the direction of electrons produced in solar neutrino interactions, demonstrated for the first time that the Sun was a source of neutrinos (without determining their flavor, though)
- The number of detected neutrinos resulted too low also for this reaction, about half of what was expected

KamiokaNDE II

- As an additional result, a year earlier, the detector KamiokaNDE-II had become sensitive enough to detect neutrinos from SN 1987A

2002 Nobel Prize in Physics

- It was awarded to M. Koshiba (Kamiokande) and Davis, but not to Bahcall, “for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”



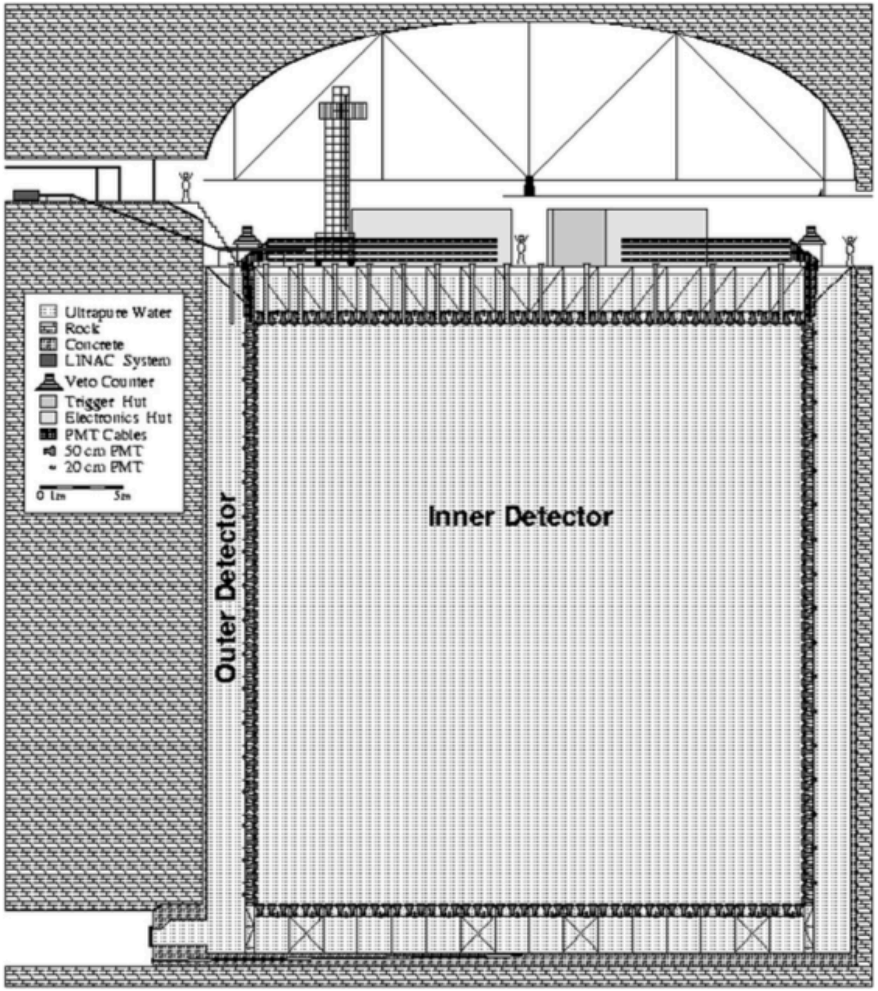
Super-Kamiokande (1996)

- Kamiokande failed to detect proton decay, and this led to the construction of Super-Kamiokande

- Super-K is a large water Cherenkov detector used to study proton decay and neutrinos from different sources including the Sun, supernovae, the atmosphere and accelerators
- The detector is located 1,000 meter underground in the Kamioka mine, Gifu, Japan

Super-K detector*

- It consists of a cylindrical stainless steel tank that is 41.4 m tall and 39.3 m in diameter holding 50,000 tons of ultra-pure water
- The tank volume is divided into an inner detector (ID) region that is 33.8 m in diameter and 36.2 m in height and outer detector (OD, in the remaining tank volume) optically separated from the ID
- Mounted on the superstructure are 11,146 PMTs 50 cm in diameter that face the ID and 1,885 20 cm PMTs that face the OD



A cross section of the Super-K detector

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* Y. Fukuda *et al.*, Nucl. Instr. and Meth. A 501 (2003) 418

Principle of operation

- A neutrino interaction with the electrons or nuclei of water can produce a charged particle that moves faster than the speed of light in water
- This creates a cone of light known as Cherenkov radiation
- The Cherenkov light is projected as a ring on the wall of the detector and recorded by the PMTs
- Using the timing and charge information recorded by each PMT, the interaction vertex and particle direction is determined

Flavor identification

- From the sharpness of the edge of the ring the type of particle can be inferred
- The multiply scattered electrons produce fuzzy rings
- Highly relativistic muons, in contrast, travel almost straight through the detector and produce rings with sharp edges
- Remind: neutrino elastic scattering produces electrons only, irrespective of neutrino flavor

Solar neutrinos (still missing)

- Super-K detected the elastic scattering reaction

$$\nu_k + e^- \rightarrow \nu_k + e^-$$

- which has a relative sensitivity to ν_e and $\nu_\mu + \nu_\tau$ of ~7:1
- The ^{8}B solar neutrino flux was calculated to be 2.40 x 10^6 cm^{-2} s^{-1}, only 0.465 of the SSM prediction

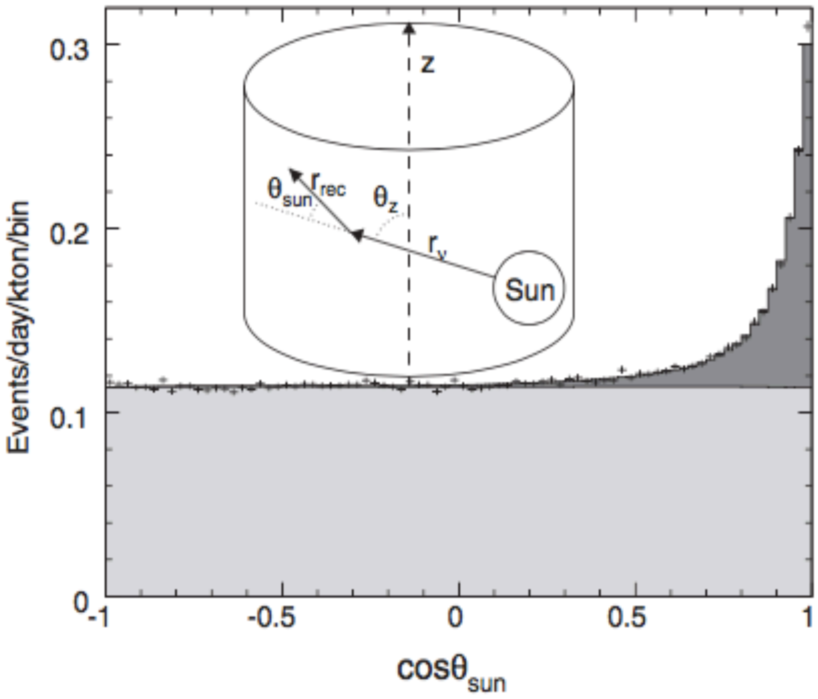


FIG. 17. Solar angle distribution for 3.49 to 19.5 MeV. $\theta_{\rm sun}$ is the angle between the incoming neutrino direction r_ν and the reconstructed recoil electron direction $r_{\rm rec}$. θ_z is the solar zenith angle. Black points are data while the histogram is the best fit to the data. The dark (light) shaded region is the solar neutrino signal (background) component of this fit.

Atmospheric neutrinos

- Atmospheric neutrinos have an energy from tens to several hundred times bigger than solar neutrinos
- Neutrino production by cosmic rays

$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow \overline{\nu}_\mu + e^+ + \nu_e$ *and charge conjugates*

is 1 e-neutrino every 2 mu-neutrinos

- Since 1985 it was known that the measured ratio of atmospheric muonic to electronic neutrinos was <u>nearer to one than to the expected value of two</u>

The anomaly of atmospheric neutrinos

- Super-K studied the ν_μ/ν_e flux ratio by observing final state leptons produced in interactions of neutrinos on nuclei

$$\nu_k + N \rightarrow l_k + N'$$

- The flavor of the final state lepton is used to identify the flavor of the incoming neutrino
- The quantity

$$R = \frac{\left(N_{\mu-like} / N_{e-like}\right)_{DATA}}{\left(N_{\mu-like} / N_{e-like}\right)_{MC}}$$

- is expected to be 1, if the physics in the Monte Carlo simulation accurately models the data
- Super-K was able to determine the incoming direction of neutrinos sufficiently well to tell whether they came from the atmosphere, 10 km above Super-K, or from the other side of the Earth, traveling 13,000 km through the planet

Super-K results

- 1998: the number of upward going (U) atmospheric muon neutrinos (generated on the other side of the Earth) is half the number of downward going (D) muon neutrinos
- Studying the asymmetry $A = \dfrac{N_U - N_D}{N_U + N_D}$
- no significant asymmetry was observed in the *e*-like data
- the μ-like data exhibited a strong asymmetry in zenith angle at high momentum (significantly deviating from expectations)

Oscillations, at last

- Neutrino oscillations were suggested to explain such deviations
- Two-neutrino oscillation hypothesis:
  - the probability for a neutrino of energy E_ν
  - produced in a flavor state *a*
  - to be observed in a flavor state *b*
  - after traveling a distance *L* is

$$P_{a\to b} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E_\nu(GeV)}\right)$$

- θ and Δm^2 are parameters of the hypothesis

ν_μ oscillations*

Super-K examined two 2-flavor oscillation models:

$\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_e$

- The best fit to $\nu_\mu \leftrightarrow \nu_\tau$ oscillations was obtained for

$$\sin^2\theta = 1.0$$
$$\Delta m^2 = 2.2\times 10^{-3}\,eV^2$$

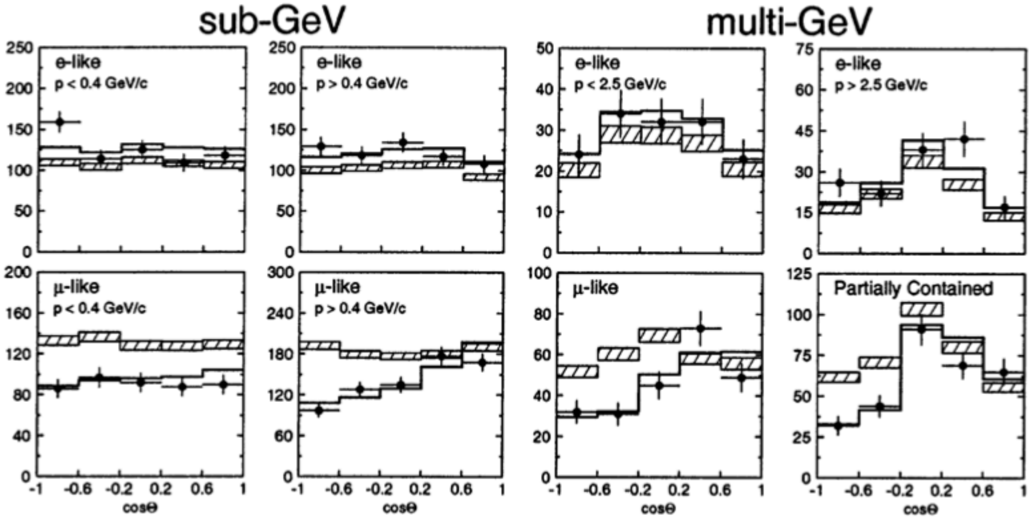


FIG. 3. Zenith angle distributions of μ-like and e-like events for sub-GeV and multi-GeV data sets. Upward-going particles have $\cos\Theta < 0$ and downward-going particles have $\cos\Theta > 0$. Sub-GeV data are shown separately for $p < 400$ MeV$/c$ and $p > 400$ MeV$/c$. Multi-GeV e-like distributions are shown for $p < 2.5$ and $p > 2.5$ GeV$/c$ and the multi-GeV μ-like are shown separately for FC and PC events. The hatched region shows the Monte Carlo expectation for no oscillations normalized to the data live time with statistical errors. The bold line is the best-fit expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the overall flux normalization fitted as a free parameter.

- The $\nu_\mu \leftrightarrow \nu_e$ oscillation hypothesis
- and the no oscillation hypothesis were both highly disfavored

(*) Y. Fukuda *et al.,* Evidence for Oscillations of Atmospheric Neutrinos, Phys. Rev. Lett. **81**, 1562 (1998).

ν_μ oscillations

- The explanation of the atmospheric neutrino anomaly is:

- upward-going muon neutrinos (the ones traversing the Earth) have oscillated into a third neutrino type, the tau neutrino *

- downward-going muon neutrinos, on the other hand, interacted inside of Super-K before they had traveled far enough to change types

* Note that the tau neutrino was directly produced only two years later in 2000

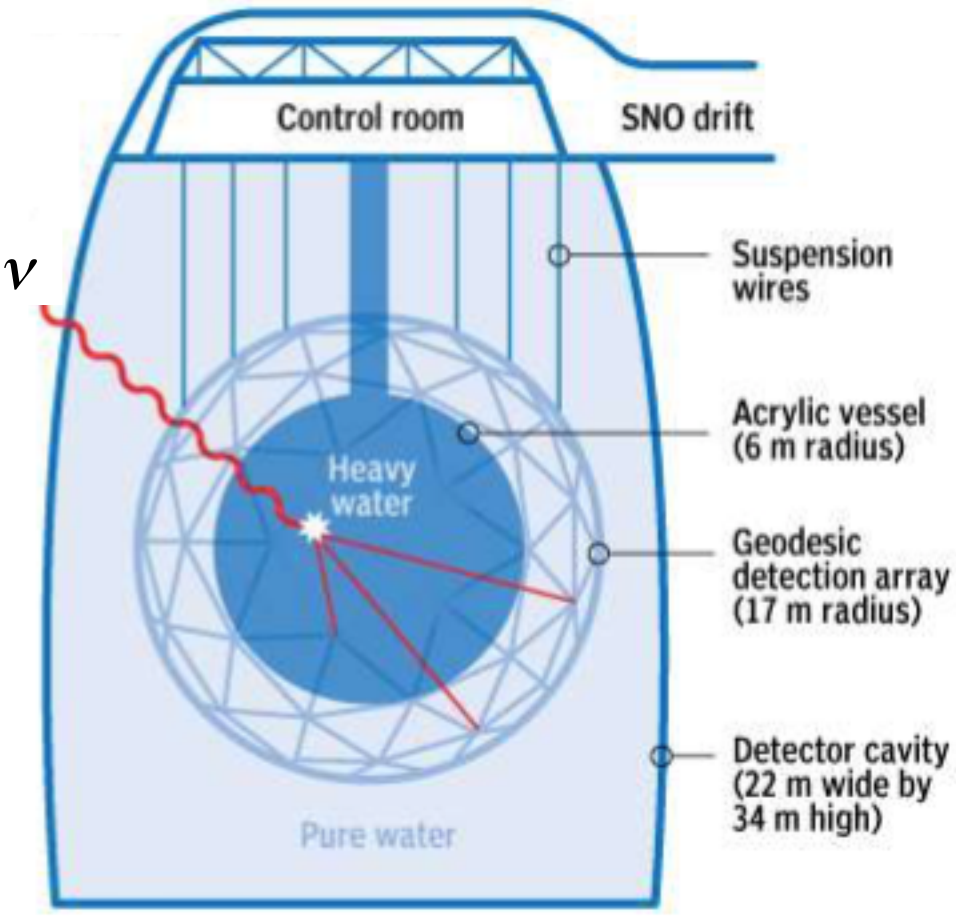
Back to the Solar Neutrino Problem

- Was Davis’ problem with electron neutrinos also due to neutrino oscillations?
- Pontecorvo and Gribov and Maki, Nakagawa and Sakata explained the solar neutrino problem from the existence of more than one kind of neutrinos
- If an electronic neutrino turns muonic in the way between Sun and Earth, it will traverse Davis’ detector without interacting
- To verify this idea, a new experiment was built 2100 m underground in a nickel mine in Sudbury, Ontario, Canada: the Sudbury Neutrino Observatory (SNO)

The SNO detector

The detector consists of 1000 tonnes of ultra-pure heavy water enclosed in a 12-m diameter acrylic plastic vessel, surrounded by 7000 tonnes of ultra-pure ordinary water contained in a 34-m high cavity of maximum diameter 22 m

Outside the acrylic vessel is a 17-m diameter geodesic sphere containing 9456 photomultiplier tubes, which detect Cherenkov light emitted as neutrinos are stopped or scattered in the heavy water



The detection rate is of the order of 10 neutrinos per day

SNO novelty*

- Cl and Ga-based experiments: exclusively sensitive to e-nu’s
- H_2O-based experiments: predominantly sensitive to e-nu’s
- SNO used heavy water (D_2O) and measured:
- the elastic scattering (ES) reaction $\boldsymbol{\nu_x + e^- \rightarrow \nu_x + e^-}$ active for all neutrino kinds but 6.4 times more sensitive to ν_e’s than to other flavors (also used by Kamiokande-II and Super-K)

$$\Phi_{ES} = \Phi(\nu_e) + 0.1559\Phi(\nu_{\mu\tau})$$

- the charged current (CC) reaction $\boldsymbol{\nu_e + d \rightarrow p + p + e^-}$ sensitive exclusively to ν_e’s (only these nu’s have enough energy to produce the associated lepton) $\Phi_{CC} = \Phi(\nu_e)$
- the neutral current (NC) reaction $\boldsymbol{\nu_x + d \rightarrow p + n + \nu_x}$ equally sensitive to all neutrino flavors $\Phi_{NC} = \Phi(\nu_e) + \Phi(\nu_{\mu\tau})$

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* A. Bellerive *et al.*, SNO Collaboration, Nucl. Phys.B 908 (2016).

Neutrino detection

- $\nu_x + e^- \rightarrow \nu_x + e^-$: ES detected by observing the cone of Cherenkov light produced by the electrons
- $\nu_e + d \rightarrow p + p + e^-$: CC also detected via the Cherenkov light produced by the electrons
- $\nu_x + d \rightarrow p + n + \nu_x$:
  - NC initially detected with pure D_2O via Cherenkov light from conversion of the 6.25 MeV γ ray produced upon neutron capture on deuterium $n + d \rightarrow {}^3H + \gamma$
  - BUT: the neutron capture cross section on deuterium is small + the γ ray energy of 6.25 MeV is near SNO’s energy threshold ➔number of NC events was low

Neutrino detection

- $\nu_x + d \rightarrow p + n + \nu_x$:
  - NC in a second phase detected with NaCl dissolved in D_2O: the thermal neutron capture cross-section for ^{35}Cl is nearly five orders of magnitude larger than that for the deuteron
  - The Q-value for radiative neutron capture on Cl is 8.6 MeV ➔ increase in the released energy led to more observable NC events
  - the cascade of prompt γ rays following neutron capture produced a Cherenkov-light hit pattern very different from that by a single relativistic electron from CC or ES reactions

The ^{8}B neutrino flux*

- Compared the flux $\Phi^{ES}(\nu_x)$ deduced from ES (assuming no neutrino oscillations), to $\Phi^{CC}(\nu_e)$ measured by CC reaction
- If neutrinos from the Sun change into other active flavors, ➔ $\Phi^{CC}(\nu_e) < \Phi^{ES}(\nu_x)$
- SNO found

$$\boxed{\Phi^{CC}(\nu_e) = 1.75} \pm 0.07(stat.)^{+0.12}_{-0.11}(sys.) \pm 0.05(theor.) \times 10^6\, cm^{-2} s^{-1}$$

$$\boxed{\Phi^{ES}(\nu_x) = 2.39} \pm 0.34(stat.)^{+0.16}_{-0.14}(sys.) \times 10^6\, cm^{-2} s^{-1}$$

- Reference to Super-K value for $\Phi^{ES}(\nu_x)$ was made because of its better precision
- The measured value of $\Phi^{CC}(\nu_e)$ is inconsistent with the null hypothesis that all observed solar neutrinos are ν_e

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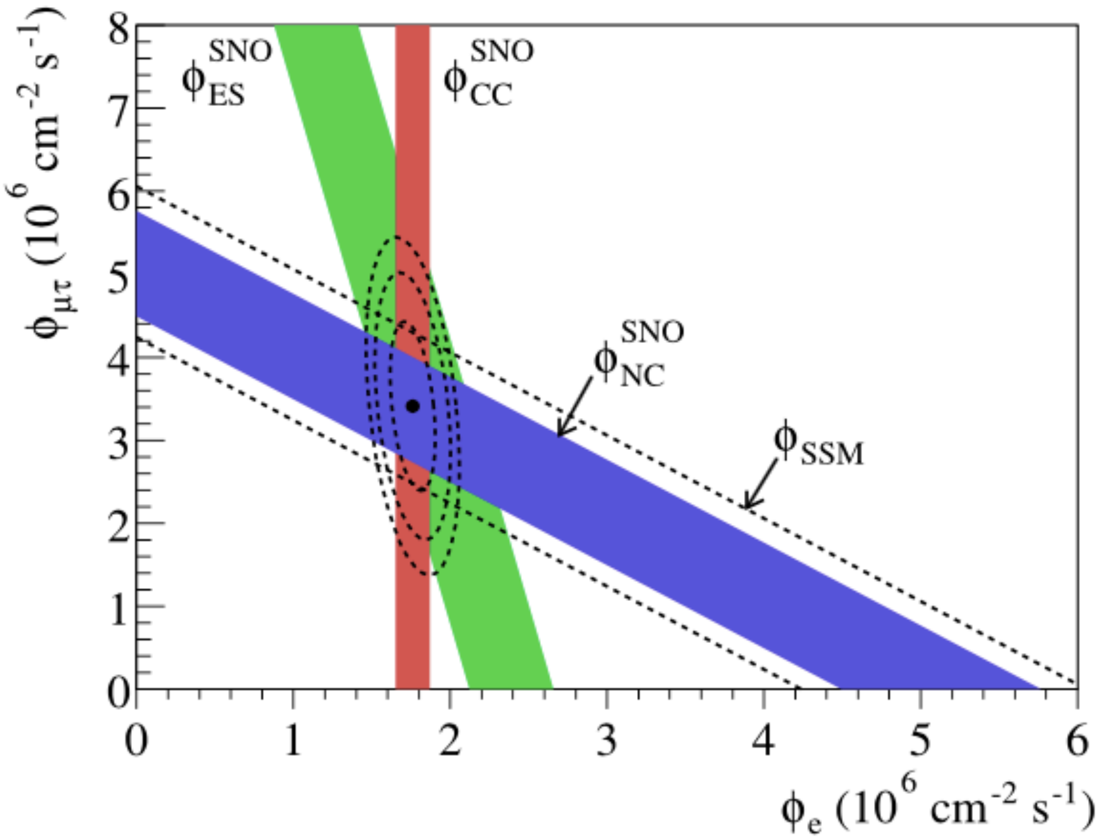
* Q. R. Ahmad *et al.*, SNO Collaboration, Phys. Rev. Lett. 87:071301 (2001).

The ^{8}B neutrino flux



Inferred flux of non-electron neutrinos $\Phi(\nu_{\mu\tau})$ against the flux of e-neutrinos $\Phi(\nu_e)$

- Best fit to $\Phi(\nu_{\mu\tau})$: 3.69±1.13 x 10^6 cm^{-2} s^{-1}
- First direct indication of a non-electron flavor component in the solar neutrino flux

- Total flux of active ^{8}B neutrinos $\Phi(\nu_x)$: 5.44±0.99 x 10^6 cm^{-2} s^{-1}
- In excellent agreement with the predictions of standard solar models

The advantage of being heavy

- SNO exploited a reaction unique to heavy water
- The use and the advantages of heavy water were proposed by H. H. Chen (1984)
- Its use provided a means to measure both electron and non-electron components, and the presence of the latter showed that neutrino flavor conversion was taking place

SNO (1999-2006)

- During 2002 and 2003 the detector was upgraded and any reference to Super-K was no longer necessary
- Although Super-K had beaten SNO on time, having published evidence for neutrino oscillation as early as 1998
- the Super-K results were not conclusive and did not specifically deal with solar neutrinos
- SNO's results were the first to directly demonstrate oscillations in solar neutrinos
- The final results were published in 2003:
- e-neutrino flux:1.75x10^{6} cm^{-2} s^{-1}
- total flux: 5.21x10^{6} cm^{-2} s^{-1}, about three times as much

Solar Neutrino Problem conclusions*

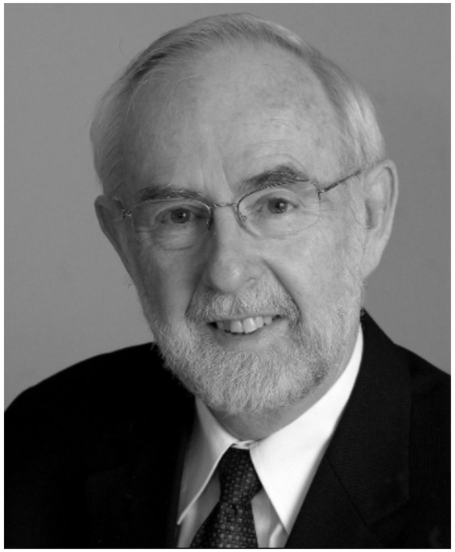
- Davis had been correctly measuring solar neutrinos for 30 years
- For 30 years people had doubted Bahcall, regarding him as ‘the guy who wrongly calculated the flux of neutrinos from the Sun’
- His calculation of solar neutrino production was correct; in his words, the agreement was

  ‘so close that it was embarrasingly close’

* F. Close, Neutrino, Oxford University Press, 2012

2015 Nobel Prize in Physics

- It was awarded to T. Kajita (Super-K) and A.B. McDonald (SNO) “for the discovery of neutrino oscillations, which shows that neutrinos have mass”



Oscillation parameters

- Neutrino mixing is expressed as a unitary transformation *U* relating the flavor and mass eigenstates
- If $|\nu_f\rangle$ represents a neutrino with definite flavor (*f* = *e*, μ, τ, …)
- and $|\nu_m\rangle$ a neutrino with definite mass (*i* = 1, 2, 3, ⋯)
- in the 3-neutrino scenario, the transformation reads

$$|\nu_m\rangle = \sum_{f=e,\mu,\tau} U_{fm} |\nu_f\rangle \qquad |\nu_f\rangle = \sum_{m=1,2,3} U^*_{fm} |\nu_m\rangle$$

PMNS matrix

- U_{fm} is the Pontecorvo-Maki-Nakagawa-Sakata matrix
- Neglecting a possible Majorana character of neutrinos, *U* is written

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- If experiment shows this matrix to be not unitary a new neutrino (sterile neutrino) is required
- If δ is non-zero neutrino oscillation violates CP symmetry

New parameters, new experiments

- The existence of oscillations brought into physics 9 new parameters in a stroke:
  - the three neutrino masses: m_1 , m_2 , m_3
  - the three mixing angles: θ_{12} , θ_{23} , θ_{13}
  - the CP-violation phase: δ
  - and two Majorana phases
- All these parameters are absent from the Standard Model for elementary particles, which, for this reason needs to be extended
- A host of new experiments was conceived, reactor, accelerator and cosmic neutrino experiments, aimed at studying the new parameters

More neutrino experiments

experiment	site	additional site	goal	source	begin oper	end oper
CUORE	Gran Sasso, IT	–	$0\nu\beta\beta$	Te130	2016	
Borexino	Gran Sasso, IT	–	Be7 sun n flux	sun	2007	
SOX	Gran Sasso, IT	–	n_e,an_e oscillation	Cr51 Ce144	2017	
Daya Bay	Daya Bay, PRC	–	an_e oscillation	6 reactors		
KATRIN	Karlsruhe, GE	–	n_e mass	H3		
ICARUS						
EXO–200	WIPP, Carlsbad, NM	–	$0\nu\beta\beta$	Xe136	2011	
LSND	Los Alamos, NM	–	n_mu oscillation	beam	1993	1998
MAJORANA	Sanford, Lead, SD	–	$0\nu\beta\beta$	Ge76	2015	
MicroBooNE	Fermilab, IL	–	MiniBooNE check	beam	2015	
MiniBooNE	Fermilab, IL	–	n_mu –> n_e	beam	2002	
MINERvA	Fermilab, IL	–	nu scattering	beam	2010	
MINOS	Fermilab, IL	Soudan, MN +735	n_mu oscillation	beam	2005	2012
MINOS+	Fermilab, IL	"	"	"	2013	2016
NOvA	Fermilab, IL	Ash River, MN +810	n_mu–>n_e	beam	2014	
DUNE	Fermilab, IL	Sanford, Lead, SD +1300	n_mu oscillation	beam	2022	
SciBooNE	Fermilab, IL	–	MiniBooNE aux	beam	2008	
SBND						
SNO	Sudbury, CA	–	n_e oscillation	sun	1999	2006
SNO+	Sudbury, CA	–	$0\nu\beta\beta$	Te130	2016	
Kamiokande II	Kamioka, JP	–		sun, atmosphere	1985	1995
Super-K	Kamioka, JP	–		sun, atmosphere	1996	
K2K	Tsukuba, JP	Kamioka, JP +250	n_mu -> n_tau	beam	1999	2004
T2K	Tokai-280m, JP	Kamioka, JP +295	n_mu -> n_e	beam	2010	
IceCube	South Pole	–		cosmos	2010	
Antares	Toulon, FR	–	n flux	cosmos	2008	
Chooz	Chooz, FR	–	an_e oscillation	2 reactors		
Double Chooz	Chooz, FR	–	an_e oscillation	2 reactors		

References

- Most of the material in the presentation was found in the beautiful book ‘Neutrino’ by Frank Close, Oxford University Press

- Physicist portraits were downloded from the web

- Much useful information was found on Wikipedia pages – support Wikipedia!