The Solar Neutrino Puzzle

Frank Filthaut

Radboud Universiteit Nijmegen / Nikhef

7 April 2008

Birth of the Neutrino

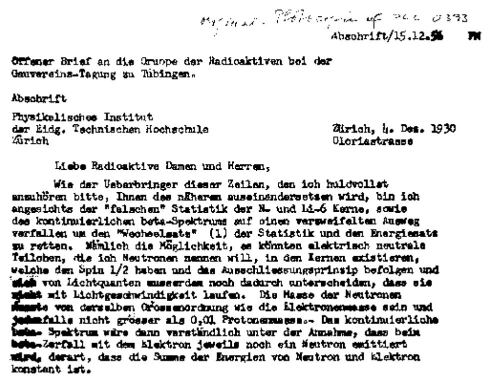
Problem (Chadwick & Ellis, 1914) in β decay $N \to N' + e^-$: the electron energy spectrum is continuous! For a general two-body decay $A \to B + C$ it is straightforward to compute that the energy of particle B is given by

$$E_B = \frac{(m_A^2 + m_B^2 - m_C^2)c^2}{2m_A}$$

hence the energies are fixed. But only N', e^- observed?!

Pauli (1930): assume existence of a neutral, spin-1/2 particle (spin discovered in 1925) with mass $m \ll m_p$: the neutrino $\nu^\ddagger$

‡after Chadwick (1932) claimed the name "neutron"



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

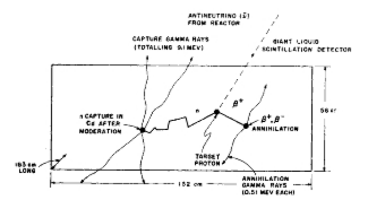
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Neutrinos and Anti-Neutrinos

Anti-neutrinos (defined as the particles liberated in the fission of neutron-rich uranium, *i.e.*, $n \rightarrow p + e^- + \bar{\nu}_e$) were observed first by Reines and Cowan (1959) at the Savannah River nuclear power plant.



With $10^{13} cm^{-2} s^{-1}$: 36 interactions per hour! Very low rates observable at all (on top of backgrounds) due to specific experimental signature

Anti-neutrinos were identified in this experiment through the reaction $\bar{\nu}_e + p \rightarrow n + e^+$:

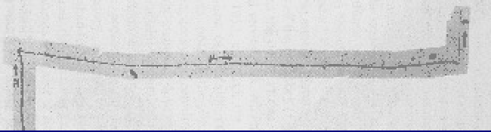
- β^+ radiation: annihilation with electrons $\Rightarrow$two 511 keV photons
- neutron capture by Cd, followed by de-excitation: *delayed* coincidence

Davis and Harmer (1959) looked for $\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ but did not observe it

Neutrinos and anti-neutrinos are different particles!

Birth of Particle Physics

Since V. Hess's balloon flights in 1912: cosmic rays
(seen here in emulsion: energy loss by charged particles used to visualize their trajectories)



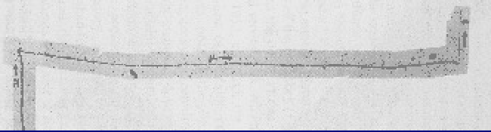
Yet another source of "missing momentum"!
Interpretation (Powell *et al.*, 1947): decays of new particles

- $\pi^{\pm} \to \mu^{\pm}\nu$
- $\mu^{\pm} \to \mathrm{e}^{\pm}\nu\nu$

Many more (generally heavier) particles have been discovered in cosmic rays.

Birth of Particle Physics

Since V. Hess's balloon flights in 1912: cosmic rays
(seen here in emulsion: energy loss by charged particles used to visualize their trajectories)



Yet another source of "missing momentum"!
Interpretation (Powell *et al.*, 1947): decays of new particles

- $\pi^\pm \rightarrow \mu^\pm \nu$
- $\mu^\pm \rightarrow \mathrm{e}^\pm \nu \nu$

Many more (generally heavier) particles have been discovered in cosmic rays. Quoting from Lamb's (1955) Nobel speech:

> "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine"

Neutrino Types

With the advent of high-energy particle accelerators (since early fifties), controlled experiments have become possible. Example:

If there were only one type of neutrino, high-energy ν would lead to the production of muons and electrons in similar amounts. This was tested in the early 60's at the AGS in Brookhaven using neutrinos from $\pi^{\pm}$ decay

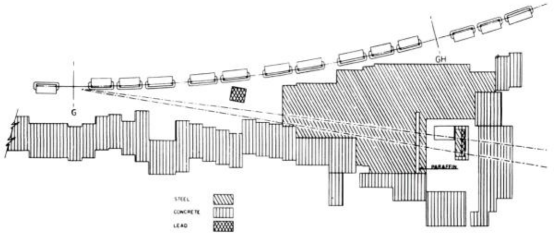


FIG. 1. Plan view of AGS neutrino experiment.

Observation: only muons were produced $\Rightarrow$
there is more than one neutrino type: $\nu_\mu \neq \nu_e$

What have we learned?

A selection of important results. . .

- most particles discovered in cosmic ray events and (later) in accelerator-based experiments are not "fundamental" but composite particles, consisting of quarks (and/or anti-quarks)
  - this is true for p, n (but not for the electron)
- there appear to be four fundamental forces or interactions in Nature:

gravity: this holds our feet on the ground, Earth in its orbit around the Sun, etc.

electromagnetism: responsible for the most "visible" phenomena (all molecular interactions, existence of solids and liquids, . . .)

strong interaction: needed to hold protons and neutrons together in nuclei – but also the quarks in a proton or neutron

weak interaction: responsible for a large fraction of the possible nuclear transmutation processes, and in particular for fusion processes in the Sun and other stars

The Standard Model

The Standard Model of particle physics (Glashow, Salam, Weinberg, '67) captures our collected wisdom about particles and their interactions:
Matter particles (for each particle there is a corresponding antiparticle):

	charge	family 1	family 2	family 3
leptons	0 $-e$	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$
quarks	$+2/3e$ $-1/3e$	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$

Interactions are not "instantaneous" (this would violate Special Relativity) but are mediated by so-called gauge bosons:

electromagnetism: photon (light!)

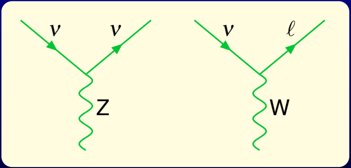
strong interaction: gluons

weak interactions: Z, $W^{\pm}$

More on Interactions

Knowing the interactions allows us to compute relevant quantities (lifetimes of unstable particles, interaction cross sections). The various couplings can be represented graphically using Feynman diagrams (which are useful also for these computations). Example:

The neutrinos only interact with the Z and $W^{\pm}$ bosons mediating the weak interaction:



- the interaction with the Z ($W^{\pm}$) boson is also called Neutral Current (Charged Current)
- the weak interaction is "weak" because the Z, $W^{\pm}$ are heavy!
  (in contrast to the massless γ, g)

"Building blocks" such as these can be used to construct complete interaction processes

Outstanding Questions

1. How can we be massive?
   $\Rightarrow$ the fact that particles (leptons, quarks, but also the W and Z bosons) can have mass at all is as yet unexplained. We have a working hypothesis (the Higgs mechanism) but it implies the existence of a thus far unobserved particle: the Higgs boson

Outstanding Questions

1. How can we be massive?
   $\Rightarrow$ the fact that particles (leptons, quarks, but also the W and Z bosons) can have mass at all is as yet unexplained. We have a working hypothesis (the Higgs mechanism) but it implies the existence of a thus far unobserved particle: the Higgs boson
2. So what about gravity??
   $\Rightarrow$ on theoretical grounds, the Standard Model cannot incorporate it! This may also affect the "stability" of our Standard Model proper, and new mechanisms are being studied to address these issues (Supersymmetry)

Outstanding Questions

1. How can we be massive?
   $\Rightarrow$ the fact that particles (leptons, quarks, but also the W and Z bosons) can have mass at all is as yet unexplained. We have a working hypothesis (the Higgs mechanism) but it implies the existence of a thus far unobserved particle: the Higgs boson
2. So what about gravity??
   $\Rightarrow$ on theoretical grounds, the Standard Model cannot incorporate it! This may also affect the "stability" of our Standard Model proper, and new mechanisms are being studied to address these issues (Supersymmetry)
3. Why is the Universe filled with matter?
   $\Rightarrow$ starting from a Big Bang, it would be more natural for matter and anti-matter particles to annihilate, leaving only photons! We understand one mechanism that causes a matter/anti-matter asymmetry, but it is not sufficient to explain our Universe

Outstanding Questions

1. How can we be massive?
   $\Rightarrow$ the fact that particles (leptons, quarks, but also the W and Z bosons) can have mass at all is as yet unexplained. We have a working hypothesis (the Higgs mechanism) but it implies the existence of a thus far unobserved particle: the Higgs boson
2. So what about gravity??
   $\Rightarrow$ on theoretical grounds, the Standard Model cannot incorporate it! This may also affect the "stability" of our Standard Model proper, and new mechanisms are being studied to address these issues (Supersymmetry)
3. Why is the Universe filled with matter?
   $\Rightarrow$ starting from a Big Bang, it would be more natural for matter and anti-matter particles to annihilate, leaving only photons! We understand one mechanism that causes a matter/anti-matter asymmetry, but it is not sufficient to explain our Universe
4. Are neutrinos their own anti-particles?
   $\Rightarrow$ this is not possible for other matter particles, but it would help greatly to address the previous issue

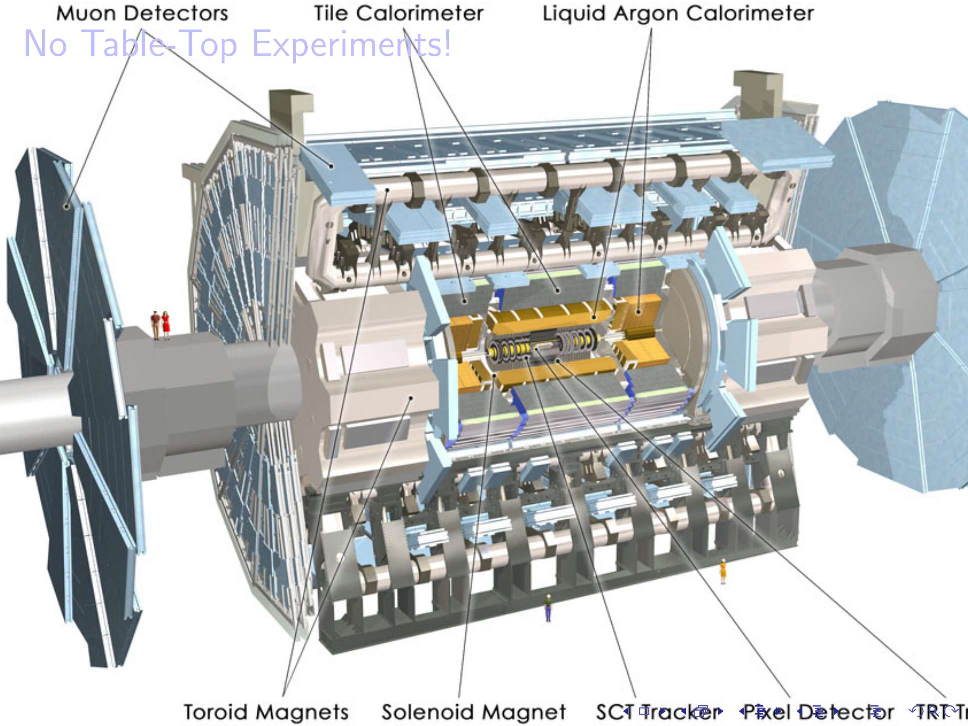
The High-Energy Frontier

In a few months from now, the Large Hadron Collider at CERN (Geneva) will start operation

1. accelerate intense beams of protons to energies of 7 TeV ($v = 0.9999991c$)
2. make these protons collide head-on in the centre of a detector
3. observe the outcome of the interactions

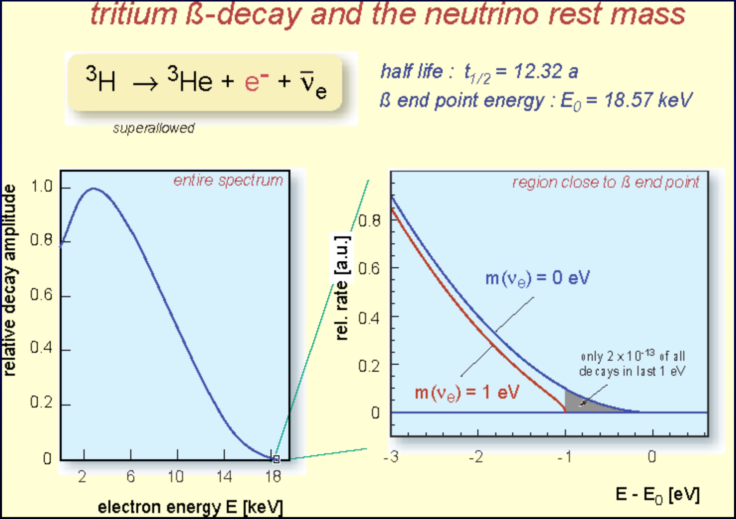
Aim: find new particles like the Higgs boson or evidence of Supersymmetry, and walk away with a Nobel Prize

No Table-Top Experiments!



Neutrino Masses: experiment

Decay kinematics have been used for half a century to try and measure neutrino masses: the electron energy spectrum (mostly for ^3H decay)



Neutrino Masses: experiment

The latest attempt is the Karlsruhe tritium neutrino (Katrin) experiment:
expected sensitivity ~ 0.2 eV

arrival of Katrin spectrometer

The Sun

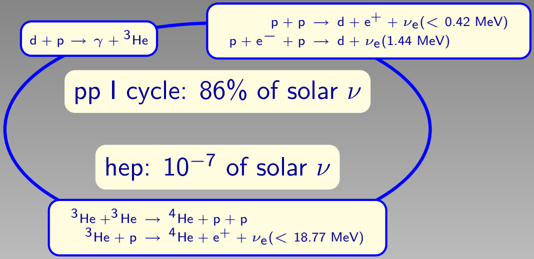
What makes stars like our Sun shine?

1. accretion of mass
2. collapse due to gravitation
3. increase of pressure and temperature $\Rightarrow$

Ignition of stellar burning: nuclear fusion

These processes are known and part of the Standard Solar Model (Bahcall *et al.*) dating from the 60's but refined since then

Primary Fusion Processes in the Sun



Primary Fusion Processes in the Sun

$d + p \longrightarrow \gamma + {}^3\text{He}$

$p + p \longrightarrow d + e^+ + \nu_e(< 0.42\ \text{MeV})$

$p + e^- + p \longrightarrow d + \nu_e(1.44\ \text{MeV})$

pp I cycle: 86% of solar ν

hep: 10^{-7} of solar ν

${}^3\text{He} + {}^3\text{He} \longrightarrow {}^4\text{He} + p + p$

${}^3\text{He} + p \longrightarrow {}^4\text{He} + e^+ + \nu_e(< 18.77\ \text{MeV})$

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

${}^7\text{Li} + p \longrightarrow {}^4\text{He} + {}^4\text{He}$

pp II cycle: 14% of solar ν

${}^7\text{Be} + e^- \longrightarrow {}^7\text{Li} + \nu_e(0.861\ \text{MeV})$

Primary Fusion Processes in the Sun

$\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{d} + \mathrm{e}^{+} + \nu_{\mathrm{e}}(< 0.42\ \mathrm{MeV})$

$\mathrm{p} + \mathrm{e}^{-} + \mathrm{p} \longrightarrow \mathrm{d} + \nu_{\mathrm{e}}(1.44\ \mathrm{MeV})$

$\mathrm{d} + \mathrm{p} \longrightarrow \gamma + {}^{3}\mathrm{He}$

pp I cycle: 86% of solar ν

hep: 10^{-7} of solar ν

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \longrightarrow {}^{4}\mathrm{He} + \mathrm{p} + \mathrm{p}$

${}^{3}\mathrm{He} + \mathrm{p} \longrightarrow {}^{4}\mathrm{He} + \mathrm{e}^{+} + \nu_{\mathrm{e}}(< 18.77\ \mathrm{MeV})$

${}^{8}\mathrm{Be}^{*} \longrightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$

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

pp III cycle: $1.5 \cdot 10^{-4}$ of solar ν

${}^{8}\mathrm{B} \longrightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{e}^{+} + \nu_{\mathrm{e}}(< 14.06\ \mathrm{MeV})$

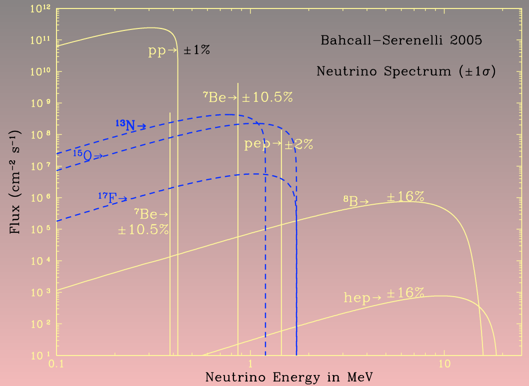
${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \longrightarrow {}^{7}\mathrm{Be} + \gamma$

${}^{7}\mathrm{Li} + \mathrm{p} \longrightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$

pp II cycle: 14% of solar ν

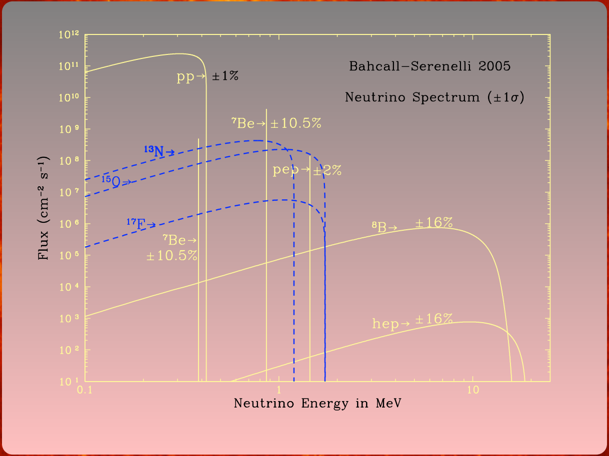
${}^{7}\mathrm{Be} + \mathrm{e}^{-} \longrightarrow {}^{7}\mathrm{Li} + \nu_{\mathrm{e}}(0.861\ \mathrm{MeV})$

The Resulting Neutrino Spectrum



Total neutrino flux on Earth: $\sim 6 \cdot 10^{10} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (!!!)

The Resulting Neutrino Spectrum



Total neutrino flux on Earth: $\sim 6 \cdot 10^{10}\text{cm}^{-2}\text{s}^{-1}$ (!!!)

. . . but don't worry: < 1 interaction/s per human body

The Homestake Experiment

Ray Davis set out ('64) to test the Standard Solar Model's predictions.

- radiochemical: capture process

$$\nu_e + ^{37}\text{Cl} \to ^{37}\text{Ar} + e^-,$$

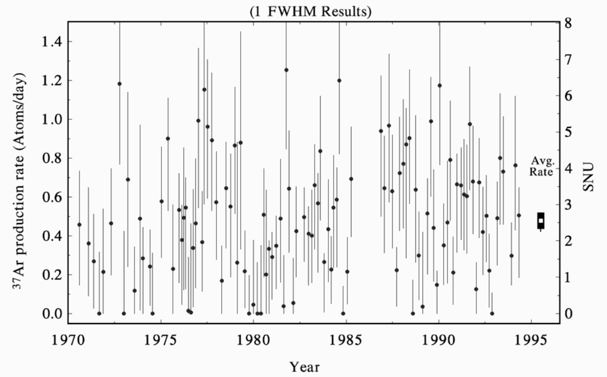
$E_\nu > 0.814$ MeV (^{7}Be ν_e)

- with 400,000 l C_2Cl_4: expected to observe 1.5 interaction per day
- Homestake gold mine (South Dakota): 1.5 km depth to shield the experiment from backgrounds
- painstaking procedure to filter ^{37}Ar atoms and observe their decays

An experiment that lasted 35 years!

The Homestake Experiment

Results from the experiment: only $\sim 1/3$ of the expected flux observed



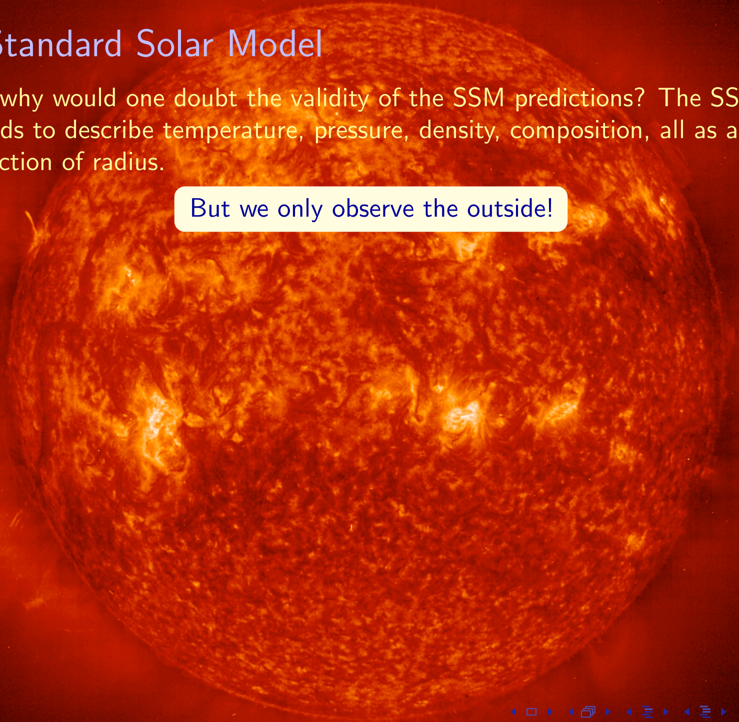
Clearly, there was a problem. But where: in the physics, the measurement, or in the flux predictions?

- Later, other radiochemical experiments ($^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$, $E_\nu > 0.232$ MeV) also observed deficits (observed fraction ~ 0.55)

The Standard Solar Model

So why would one doubt the validity of the SSM predictions? The SSM needs to describe temperature, pressure, density, composition, all as a function of radius.

But we only observe the outside!

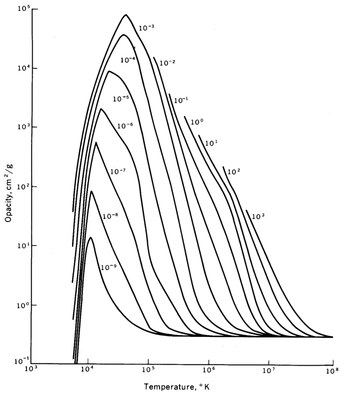


The Standard Solar Model

So why would one doubt the validity of the SSM predictions? The SSM needs to describe temperature, pressure, density, composition, all as a function of radius.

But we only observe the outside!

- Part of it is really simply physics...
  - relations between density profile and pressure, *etc.*
- But in particular the temperature profile depends very much on absorption in the Sun's atmosphere
  - this itself depends on a detailed knowledge of microscopic physics processes, as well as composition
  - these are partly calculated and partly measured in the laboratory
- And the ^{7}Be and ^{8}B ν production processes depend on temperature as T^{11} and T^{25}, respectively!



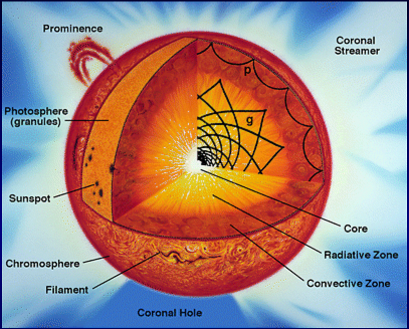
curves for different ρ

Helioseismology to the Rescue

The Sun's surface is not static!

Helioseismology to the Rescue

The Sun's surface is not static!



Sound waves of different angular momentum probe the density at different radii!

The density profile as measured using helioseismology is in good agreement with the SSM predictions

The Neutrino Oscillation Formalism

The Standard Model *does* in fact allow for massive neutrinos

- fermion masses are generated dynamically through an interaction with the Higgs field: this interaction need not be "flavour diagonal"
- the resulting mass matrix can be diagonalized, so as to yield mass eigenstates which are linear superpositions of flavour eigenstates: $\nu_i = \sum_\alpha U_{i\alpha}\nu_\alpha$

All this is *exactly* analogous to the well-known phenomenon of quark mixing, but with two important practical differences:

1. unlike quarks, neutrinos exist as free particles
2. the neutrino masses (and therefore also the mass differences) are much smaller $\Rightarrow$ neutrinos propagate coherently over macroscopic (even astronomic) distances

The Neutrino Oscillation Formalism

If now a ν_e of given momentum p is created at time $t = 0$, the amplitude that at some later time t it will still manifest itself as a ν_e is

$$A_{ee} \equiv A(\nu_e \to \nu_e) = \sum_i U_{ie}^* e^{-iE_i t/\hbar} U_{ie}$$

In quantum mechanics, it's the |square| of the amplitude that matters!

The Neutrino Oscillation Formalism

If now a ν_e of given momentum p is created at time $t = 0$, the amplitude that at some later time t it will still manifest itself as a ν_e is

$$A_{\mathrm{ee}} \equiv A(\nu_\mathrm{e} \to \nu_\mathrm{e}) = \sum_i U^*_{ie} e^{-iE_i t/\hbar} U_{ie}$$

In quantum mechanics, it's the |square| of the amplitude that matters!

For simplicity, consider only two neutrino species, and

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

For ultrarelativistic neutrinos, one can approximate

$$E_i = \sqrt{p^2c^2 + m_i^2c^4} \approx pc + \frac{m_i^2c^3}{2p}$$

Filling in all the numbers, one obtains

$$\begin{aligned} P_{\mathrm{ee}} &= |A_{\mathrm{ee}}|^2 \\ &\approx 1 - \sin^2 2\theta \sin^2\left(\frac{(m_1^2 - m_2^2)c^3 t}{4p\hbar}\right) \\ &\approx 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E) \end{aligned}$$

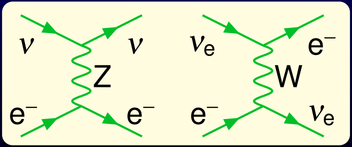
(E in GeV, L in km, m^2 in eV^2)

Small Δm^2 require large L!

The SNO Principle

Basic reactions in normal matter:

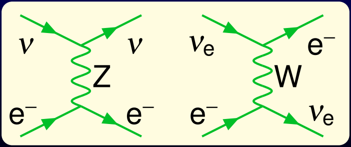
- CC: $\nu_e + n \rightarrow e^- + p$
  (this works only for ν_e: the ν are not sufficiently energetic to produce μ or τ)
- NC: $\nu + n, p \rightarrow \nu + n, p$
  (for all three ν)
- ES: $\nu + e^- \rightarrow \nu + e^-$
  (possible for all three ν, but cross section for $\nu_e \sim 6$ times as high as for ν_μ, ν_τ)



The SNO Principle

Basic reactions in normal matter:

- CC: $\nu_e + n \to e^- + p$
  (this works only for ν_e: the ν are not sufficiently energetic to produce μ or τ)
- NC: $\nu + n, p \to \nu + n, p$
  (for all three ν)
- ES: $\nu + e^- \to \nu + e^-$
  (possible for all three ν, but cross section for $\nu_e \sim 6$ times as high as for ν_μ, ν_τ)



From the proposal by H. Chen (1985):

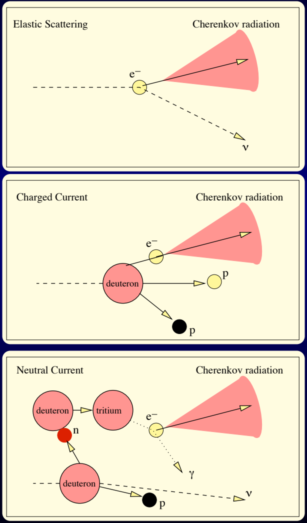
> An experiment which directly addresses the solar-neutrino problem should be sensitive to all neutrino species equally. Such a measurement could determine the total solar-neutrino flux *even if neutrinos oscillate.*

- we need an experiment that can measure Neutral Current as well as Charged Current events
- . . . but the ν usually carries most of the energy $\Rightarrow$ very hard to observe!
- the exception: ν-induced disintegration of the deuteron

Use heavy water: D_2O

The Detection Strategy

The three different interactions manifest themselves differently:



ES: an electron receives a significant amount of energy and travels roughly in the direction of the incoming ν_e. It loses energy mainly through Cherenkov radiation ($\sim$ shock wave).

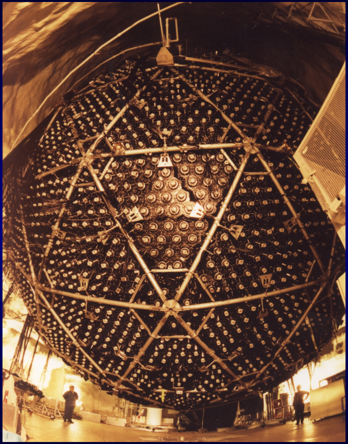
CC: the neutrino is transformed to a (high-energy) electron (but $\sim$ without the directional correlation). The protons remain undetected.

NC: the neutrino splits the deuteron, and the liberated neutron leads to the formation of an excited triton. The triton decays to its ground state through the emission of a 6.25 MeV photon. The photon collides with atomic electrons.

Down to Earth

The Sudbury Neutrino Observatory: design

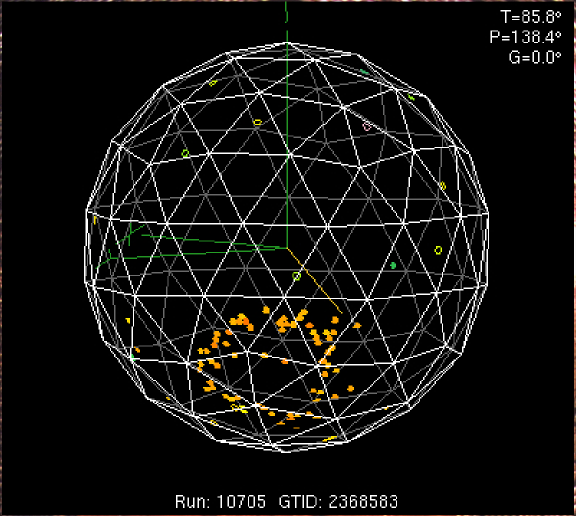
- heavy water: available in large quantities in Canada (but representing $\sim$ Cnd\$ 300M, on loan from AECL)
- radiation free environment: as in the Homestake experiment, the experiment is quite susceptible to other sources of radiation than neutrinos (radioactive materials, decays from cosmic rays)
$\Rightarrow$ 2 km underground!
- good photodetection capabilities: use $\sim$ 10,000 PMTs of diameter 20 cm to cover the inside of a 12 m diameter acrylic vessel



Support structure with PMTs

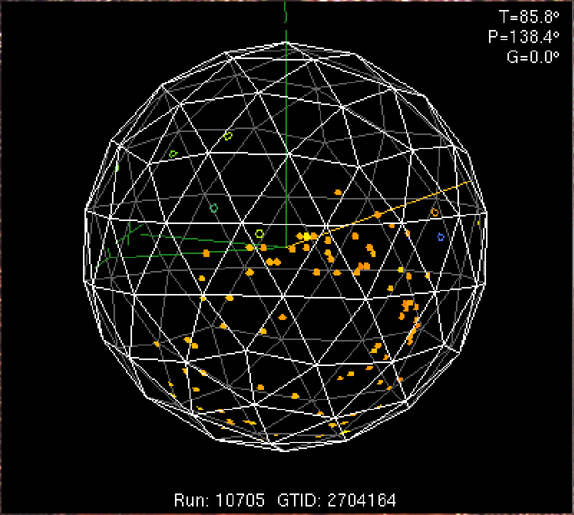
Some Candidate Events

Colour coding: PMT hit time relative to trigger timestamp



Some Candidate Events

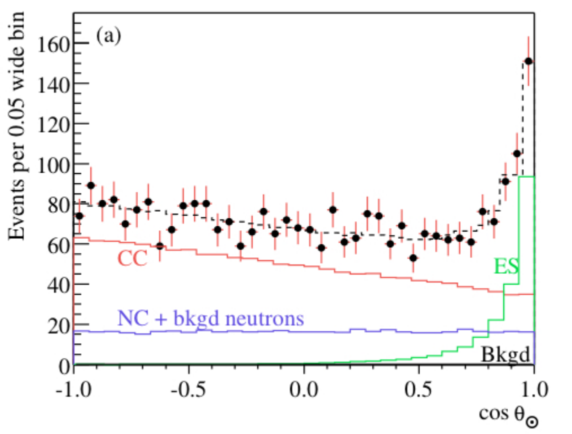
Colour coding: PMT hit time relative to trigger timestamp



Results: event distributions

The three interactions can be distinguished only statistically!

- Angle between Cherenkov cone direction and the Sun

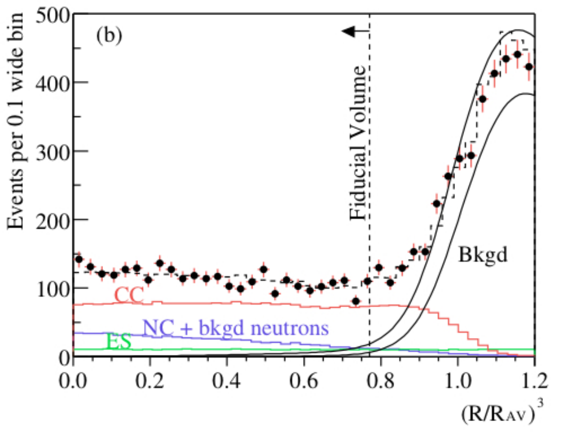


It is assumed that the shapes of the distributions for the different processes are known; their relative contributions are fit

Results: event distributions

The three interactions can be distinguished only statistically!

- Radial coordinate of the reconstructed interaction point

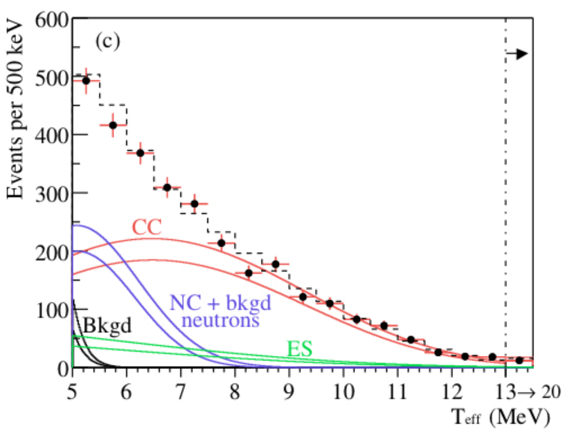


It is assumed that the shapes of the distributions for the different processes are known; their relative contributions are fit

Results: event distributions

The three interactions can be distinguished only statistically!

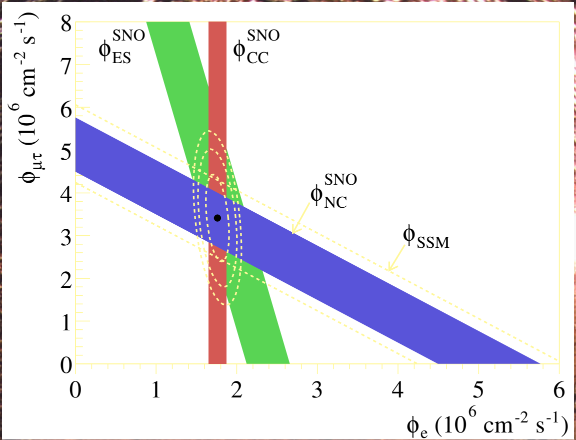
- Reconstructed energy



It is assumed that the shapes of the distributions for the different processes are known; their relative contributions are fit

Evidence for Oscillations

Using the total cross sections for the individual processes, a flux determination can be made:



The data are incompatible with the absence of ν_μ, ν_τ $\Rightarrow$ evidence for neutrino oscillations!

Missing Details

This talk isn't complete!

- I haven't mentioned the atmospheric neutrino anomaly: a deficit of ν_μ, $\bar{\nu}_\mu$ in decay chains of cosmic rays impinging on the atmosphere. This provided the first indication for neutrino oscillations (Super-Kamiokande, 1998)

Missing Details

This talk isn't complete!

- I haven't mentioned the atmospheric neutrino anomaly: a deficit of ν_μ, $\bar{\nu}_\mu$ in decay chains of cosmic rays impinging on the atmosphere. This provided the first indication for neutrino oscillations (Super-Kamiokande, 1998)
- The mass difference relevant to the solar neutrino deficit is $\Delta m^2 \approx 7 \cdot 10^{-5}\mathrm{eV}^2$ (estimated more precisely using ν_e *disappearance* experiments near nuclear reactors). The "atmospheric" analogue is $\Delta m^2 \approx 2 \cdot 10^{-3}\mathrm{eV}^2$ (proper procedure: global fit to 3 families, many experiments)

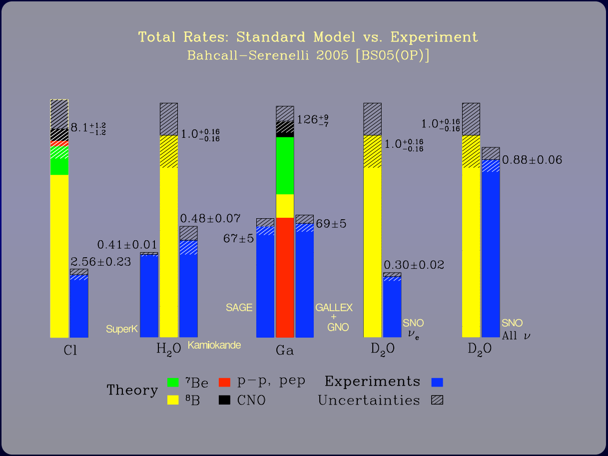
Missing Details

This talk isn't complete!

- I haven't mentioned the atmospheric neutrino anomaly: a deficit of ν_μ, $\bar{\nu}_\mu$ in decay chains of cosmic rays impinging on the atmosphere. This provided the first indication for neutrino oscillations (Super-Kamiokande, 1998)
- The mass difference relevant to the solar neutrino deficit is $\Delta m^2 \approx 7 \cdot 10^{-5}\text{eV}^2$ (estimated more precisely using ν_e *disappearance* experiments near nuclear reactors). The "atmospheric" analogue is $\Delta m^2 \approx 2 \cdot 10^{-3}\text{eV}^2$ (proper procedure: global fit to 3 families, many experiments)
- Using only oscillations in vacuum, it isn't possible to explain $P_{ee} < 0.5$. This needs the Mikheyev-Smirnov-Wolfenstein or MSW effect, affecting the propagation of neutrino states in matter due to the presence of (large densities of) electrons
  - this explains why the Gallium experiments found a smaller deficit (on average, smaller E_ν)

Bottom Line

Compare again the measurements with theory predictions:



Very satisfactory agreement!

Conclusions

- The Standard Solar Model has withstood 40 years of scrutiny
  - the (total) observed ν flux is now used to estimate the temperature in the Sun's core!
- SNO (and Super-Kamiokande) have convinced the world that neutrino oscillations are for real!
- A deeper understanding of the nature of neutrinos may be the key to understanding the matter–antimatter asymmetry
  - information may come either from the high-energy frontier (LHC) or from experiments conducting dedicated studies of neutrinos