SAO Project Cover Page

Project 027

Project Title Solving the Solar Neutrino Problem

Solving the Solar Neutrino Problem

Introduction

It was first postulated nearly a century ago, that the only way for our Sun to have maintained it's output for the billions of years required for Earth to have evolved, was for thermonuclear fusion to be providing the internal energy source: "…hydrogen atoms…are gradually being combined to form more complex elements, the total heat…[will] suffice for our demands…[and] combinations which liberate energy ought not to be impossible." (Eddington 1920). This proved an accurate theory, the main source of the Sun's heat now known to come from the exothermic proton-proton fusion reaction:

$$4\,{}^{1}_{1}\mathrm{H} \Longrightarrow {}^{4}_{2}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}} + 25\ \mathrm{MeV} \qquad \text{----------}\ 1$$

Note the release of two electron-neutrinos (ν_e) and 25 MeV energy (Lowe 2009).

This essay will present a summary of the nature, origin and discovery of solar neutrinos. It will then backtrack somewhat, and discuss the so-called 'solar neutrino problem' which puzzled scientists after Davis (1968) and Bahcall (1968) built a neutrino detector to test Eddington's solar nucleosynthesis theory, and found that theory wanting. A tour of the various detectors and their results/shortcomings will be followed by a short review of current and future research.

What is a neutrino?

In the Standard Model of particle physics, there are sixteen fundamental particles which cannot be split into smaller parts. Twelve of them are particles of matter, the other four are carriers of force. There is a postulated 17th particle, the Higgs Boson, which is required to impart mass to all the others (Darlingweb1).

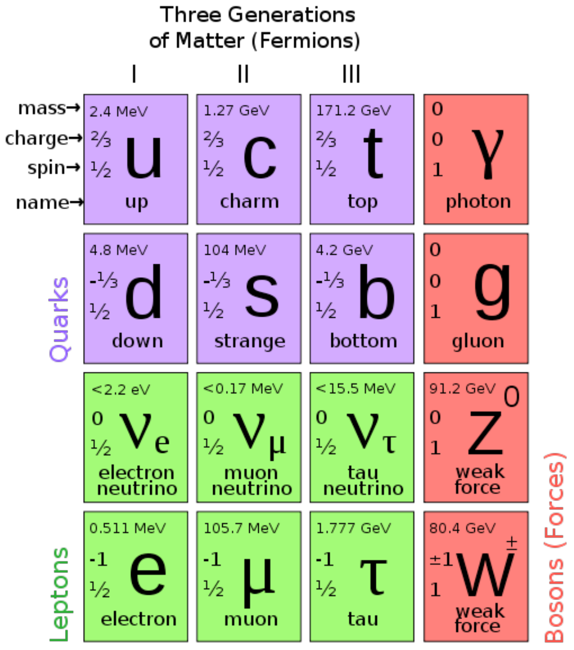


Fig. 1 Fundamental particles in the Standard Model Credit Fermilab

As seen in Figure 1, the particles of interest to us are the electron-neutrino, the muon-neutrino and the tau-neutrino. Within the model, particles can be classified according to several criteria, including their intrinsic spin, and their response to the four fundamental forces of nature. Namely gravity, electromagnetic, weak nuclear and strong nuclear. Particles with half integer spin numbers are grouped as fermions, and those with zero or integer spin numbers are grouped as bosons. Since neutrinos have spin ½, our three neutrinos are fermions of the 1st, 2nd and 3rd generation, reflecting their successive energy states.

Though gravity influences all particles, the effect is negligible, and the electromagnetic force acts only on *charged* particles. The strong nuclear force only acts on *some* particles, specifically to hold neutrons and protons together, and the weak nuclear force acts on *all* particles. So there are some particles such as neutrinos, for which the weak nuclear force is the dominant one, and these are classified as leptons. So, our neutrinos are fundamental particles with half integer spin (fermions) and responsive to the weak nuclear force (leptons) (Halliday 2005).

Though the proposal for the existence of neutrinos is attributed to Wolfgang Pauli, it was Enrico Fermi who clarified Pauli's name 'neutron' as being 'neutrino'. In a letter read out by physicist Lise Meitner, to a meeting at the Swiss Federal Institute of Technology, Zurich, on December 4th, 1930, Pauli sheepishly offered up the existence of an electrically neutral, low mass particle which was needed to balance beta decay equations and thereby maintain the law of conservation of energy. Beta decay is the radioactive transmutation of species which results in the release of an electron, the electron historically known as a beta particle. Before Pauli could publish on his new particle (in 1934), Fermi had worked out the details of the beta decay problem using Pauli's 'little neutral one', the neutrino (RHULweb).

Existence of the neutron had been inferred, but not discovered for a couple of years (Chadwick 1932), the equation in question being the decay (after about 15 minutes) of an unbound neutron into a proton and an electron. :

$$n^0 \Rightarrow p^+ + e^- \quad \text{----------} \; 2$$

But this reaction releases energy, which Pauli suggested was transmitted away by his chargeless particle, the neutrino, the equation becoming:

$$n^0 \Rightarrow p^+ + e^- + \nu_e \quad \text{----------} \; 3$$

We now know that there are three types of electrons - the 'normal' electron, which doesn't decay, and two more massive versions which decay quickly, called a muon and a tau. Each has its associated neutrino. In 1953, Pauli's electron-neutrino was discovered (Reines & Cowan 1953), in 1962, the muon-neutrino was found (Danby et al 1962), and in 1978 the tau-neutrino's existence was inferred (UCalweb), then found by Fermilab in 2000 (Fermilabweb).

Neutrinos use the Greek lowercase letter 'nu' as a symbol, with subscripts e, μ and τ to represent their electron, muon and tau partners respectively: ν_e, ν_μ, ν_τ

Using quantum mechanical nomenclature for the interchangeability of energy and mass, the mass energies of our three electrons are:

e = 511,000 eV μ = 106,600,000 eV τ = 1,777,000,000 eV

(Hyperphysweb1), and the maximum mass energies of their respective neutrinos, expressed in the same units, are:

$\nu_e < 2.2$ eV $\nu_\mu < 170,000$ eV $\nu_\tau < 15,500,000$ eV

(Kitchin 2009). The term 'neutrino' is often meant to refer to the electron-neutrino ν_e and as we'll see, the history of the solution to the solar neutrino problem is intertwined with, and complicated by, the discovery of these particles, and their properties. Comparative study of the travel time for neutrinos and photons from supernova SN1987A, showed that neutrinos travel at almost the speed of light (Lowe 2009), but given the extremely short lifespan of 2nd and 3rd generation fermions such as our ν_μ and ν_τ, it is usually taken for granted, that the Sun only emits ν_e (see below) (Princetonweb).

Neutrinos from different sources in the Sun

Nuclear reactions in the core of the Sun produce neutrinos primarily by pathways within the proton-proton chain, but also via the less significant CNO cycle.

The proton-proton chain reactions start when two protons collide, producing deuterium, a positron and a neutrino as in equation 4:

$$ {}^1_1\mathrm{H}^+ + {}^1_1\mathrm{H}^+ \Longrightarrow {}^2_1\mathrm{H} + e^+ + \nu_e \qquad \text{----------}\ 4 \qquad \text{(p.p step)} $$

This accounts for over 99% of the deuterium produced in the sun, 0.4% being produced from the fusion of two protons and an electron as in equation 5:

$$ {}^1_1\mathrm{H}^+ + e^- + {}^1_1\mathrm{H}^+ \Longrightarrow {}^2_1\mathrm{H} + \nu_e \qquad \text{----------}\ 5 \qquad \text{(p.e.p step)} $$

When these deuterium atoms fuse with another proton, helium-3 is manufactured, 15% of which undergoes fusion with a helium-4 atom to make beryllium-7. A tiny amount of this helium-3 joins with another proton and releases another neutrino:

$$ {}^3_2\mathrm{He} + {}^1_1\mathrm{H}^+ \Longrightarrow {}^4_2\mathrm{He} + e^+ + \nu_e \qquad \text{----------}\ 6 \qquad \text{(h.e.p step)} $$

Of the beryllium-7 produced, over 99% gains an electron to produce lithium-7 and a neutrino:

$$ {}^7_4Be + e^- \Longrightarrow {}^7_3Li + \nu_e \qquad \text{----------}\ 7 \qquad \text{(}^7\text{Be step)} $$

And in the final step, a tiny proportion of the beryllium-7 picks up a proton, becoming boron which then decays back to beryllium emitting yet another neutrino:

$$^{8}_{5}\mathrm{B} \Longrightarrow {}^{8}_{4}\mathrm{Be} + \mathrm{e}^{+} + \nu_{e}$$ ---------- 8 (^{8}B step)

The CNO cycle is less significant, but still contributes to neutrino production in three stages. At one point, nitrogen-13 decays into carbon-13, a positron and a neutrino as in equation 9:

$$^{13}_{7}\mathrm{N} \Longrightarrow {}^{13}_{6}\mathrm{C} + \mathrm{e}^{+} + \nu_{e}$$ ---------- 9 (^{13}N step)

Elsewhere in the cycle, oxygen-15 decays into nitrogen-15, a positron, and a neutrino as in equation 10:

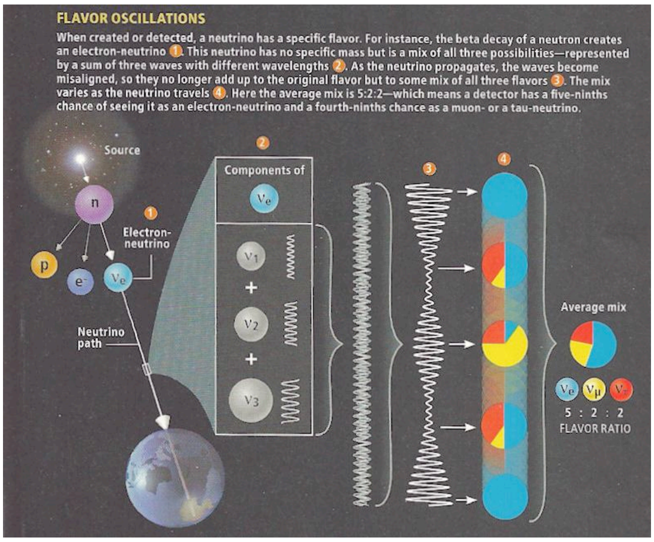
$$^{15}_{8}\mathrm{O} \Longrightarrow {}^{15}_{7}\mathrm{N} + \mathrm{e}^{+} + \nu_{e}$$ ---------- 10 (^{15}O step)

And lastly, another part of the cycle produces neutrinos by changing fluorine-17 into oxygen-17 by equation 11:

$$^{17}_{9}\mathrm{F} \Longrightarrow {}^{17}_{8}\mathrm{O} + \mathrm{e}^{+} + \nu_{e}$$ ---------- 11 (^{17}F step)

Since neutrinos are only effected by the weak nuclear force, they interact with matter extremely rarely, and so can travel away from the centre of the Sun with ease. The mean free path of a neutrino in typical solar material is some 1,000,000,000 times the solar radius (Lewis 2004), meaning they're likely to travel that far before colliding with another species. So, if we can detect them, they carry accessible, valuable information about solar core physics, compared to photons, which take the better part of a million years to escape from the Sun. The Sun produces around 2x10^{38} neutrinos per second, but a detector like NOMAD (see below) collected only enough neutrino energy in its 15 hours of active recording, to amount to 1/10 the energy of a sneeze (Fermilabweb)!

The measured, and theoretical, density of all three types of solar neutrinos reaching Earth agrees at around 6×10^{14} m^{-2} s-1 (Kitchin 2009), but they all start out as electron-neutrinos. This brings us to 'neutrino survival probability' which is a measure of the state of the neutrino at any point in time along it's journey. The probability that it is an electron-neutrino oscillates between about 14% and 100%, at the other times being equally likely to be a muon-neutrino or a tau-neutrino (Princetonweb). Another way to represent this curious feature is shown in Fig. 2, though the contemporary values are slightly different.



FLAVOR OSCILLATIONS

When created or detected, a neutrino has a specific flavor. For instance, the beta decay of a neutron creates an electron-neutrino ①. This neutrino has no specific mass but is a mix of all three possibilities—represented by a sum of three waves with different wavelengths ②. As the neutrino propagates, the waves become misaligned, so they no longer add up to the original flavor but to some mix of all three flavors ③. The mix varies as the neutrino travels ④. Here the average mix is 5:2:2—which means a detector has a five-ninths chance of seeing it as an electron-neutrino and a fourth-ninths chance as a muon- or a tau-neutrino.

Fig. 2 Depiction of how neutrino types (flavours) oscillate when observed.   Credit:??

Following Quantum Mechanical theory, where a particle can exhibit a wave-like property which can interfere with similar waves, our originating electron-neutrino acts as three self-interfering waves of mass energy. Thus, it becomes a resonant mixture of probabilities that it will be detected by an observer, as one type or another (SuperKweb). This is called ‘neutrino oscillation’ and resulted in the ‘solar neutrino problem’.

At this point, it should be noted that because of the extremely low reaction rates of neutrinos with other matter, and the consequent necessity to build very large detectors, a Solar Neutrino Unit was derived by theorists in the early 60s. A SNU is 1 neutrino interaction per second for 10^{36} target atoms (SLACweb).

The Standard Model of particle physics

A simplified understanding of the Standard Model is crucial to our later discussion of the solar neutrino problem. First generation fermions are those which obey the Pauli Exclusion principle and also don’t decay. Combinations of them are known as hadronic matter like protons and neutrons, so the left hand column of four particles in Fig. 1, exist in composites to make up our familiar world. For instance, a proton is made of two ‘up’ quarks and one ‘down’ quark (charges adding to give +1), and a neutron is made of an ‘up’, and two ‘down’ quarks (charges adding to give 0). The right hand column of force particles are those which allow interactions between other particles which are subject to the various forces of nature.

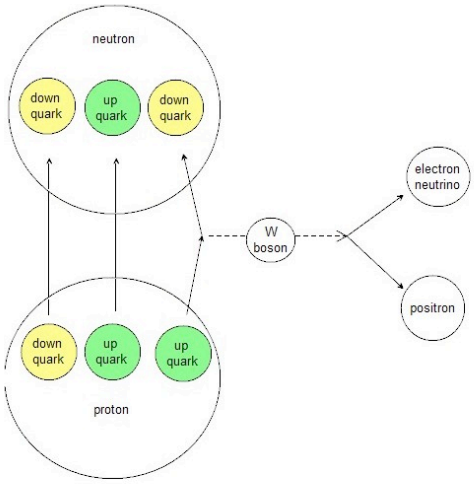


Fig. 3 Transmutation of a proton into a neutron mediated by a W boson

So, in the same way that photons facilitate electromagnetic reactions, W bosons pop in and out of existence for the short period of time required to turn an ‘up’ quark into a ‘down’ quark, thereby transmuting a proton into a neutron (Fig. 3), and resulting in the deuterium in equation 4 above (Hyperphysweb2). Equation 9 begins with unstable ^{13}N which was produced by a proton colliding with a normal ^{12}C atom in a previous stage of this suite of reactions. The ^{13}N has seven protons and six neutrons, one of the protons undergoing transmutation into a neutron in the same fashion as illustrated in Fig. 3. The same process occurs to change oxygen into nitrogen in equation 10, again releasing a neutrino.

As we’ve seen, solar neutrinos are manufactured by several decay pathways within the Sun’s core. Each of these reactions releases neutrinos of different energy levels, and so can be recorded by detectors with the appropriate sensitivity. This will also have a direct bearing on the solar neutrino problem encountered after the first detector was built. As can be seen in Fig. 4, the bulk of neutrinos are produced by the p.p reaction, but a significant proportion are also produced by the ^{7}Be reactions below 1 MeV, and the p.e.p and ^{8}B reactions above 1 MeV (Kitchin 2009, Lowe 2009).

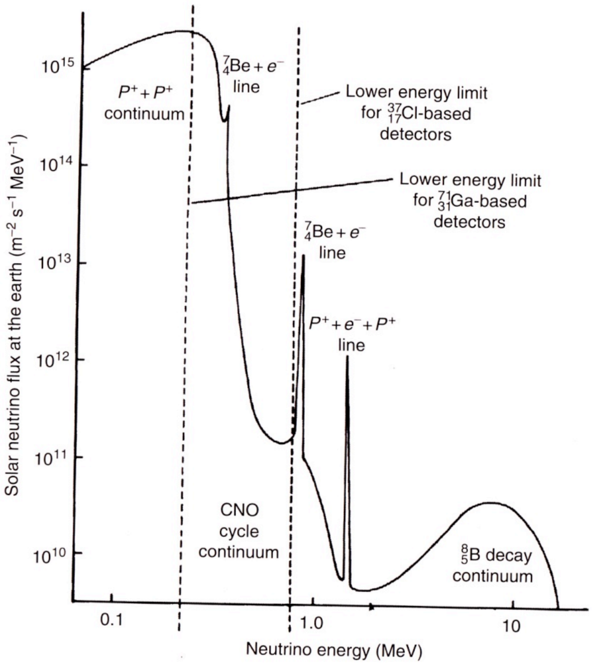


Fig. 4 Energy spectrum of neutrinos from various reactions. Credit: Kitchin

Measuring Solar Neutrinos

Now that we have some contemporary physics in hand, let's backtrack to 1968 for a history of detectors and the evolution of the 'problem'.

Pontecorvo in 1946, and Alvarez in 1949, proposed a method for detecting solar neutrinos which involved monitoring a large volume of ^{37}Cl and recording transmutations to ^{37}Ar with a consequent release of neutrinos (Bahcall 1964). This was the first neutrino detector built, and it used a volume of 100,000 gallons of tetrachloroethylene. Fig. 5 below shows the 20 ft x 48 ft cylindrical holding tank which was installed 4,850 ft below ground in a US gold mine in South Dakota, named Homestake.

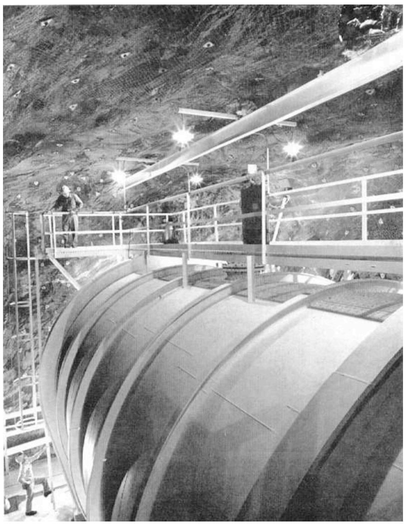


Fig. 5 First neutrino detector – South Dakota. Credit: Bahcall 1969

The reaction (Eqn 12) involved a simple transmutation of a ^{37}Cl neutron into an ^{37}Ar proton by the absorption of a neutrino. The process is mediated in exactly the same way as in Fig. 3 except that a 'down' quark is converted to an 'up' quark (Lowe 2009).

$$\nu_e + {}^{37}_{17}Cl \Rightarrow {}^{37}_{18}\mathrm{Ar} + e^- \qquad \text{---------- } 12$$

Calibrating with respect to background conversions due to cosmic rays, and extracting the ^{37}Ar by bubbling helium through the tank, Davis et al were able to calculate the number of neutrinos captured by their apparatus, and compare this to the expected rate based on theory. The expected rate was 6 SNU, but Homestake detected less than 3 SNU (Bahcall 1969). This was the 'solar neutrino problem' but the seeds of the solution were planted in Bahcall's own 1969 paper, in which he acknowledges a Russian idea that there is sufficient time and distance in a neutrino's travel from the sun, to allow it to transmute into its alternative forms (Gribov & Pontecorvo, 1969).

Subsequent neutrino detectors like the Soviet-American Gallium Experiment (SAGE), the European Gallium Experiment (GALLEX), the Japanese Kamioka neutrino detector, and the Irvine-Michigan-Brookhaven (IMB) detectors only detected electron neutrinos, and found the same mis-match between theory and observation. SAGE and GALLEX are gallium detectors, using the reaction:

$${}^{71}_{31}Ga + \nu_e \Rightarrow {}^{71}_{32}Ge + e^- \qquad \text{-------- } 13$$

With a maximum threshold of 0.236 MeV, thereby only detecting neutrinos from the p-p reaction in the sun (Fig. 4). Kamioka and IMB were water-based detectors which recorded Cerenkov radiation events caused by incoming neutrinos ricocheting off electrons, and also transmuting a proton into a neutron and a positron. These detectors were limited to about 5 MeV neutrinos (Kitchin 2009).

But then work at the American Liquid Scintillator Neutrino Detector (LSND) hinted at muon/electron neutrino oscillations (Athanassopoulos et al 1996) and so the search was on for a full explanation of the solar neutrino problem.

The breakthrough came at the turn of the century, when experiments conducted at the Japanese Super Kamiokande detector showed that some muon neutrinos produced by cosmic ray interactions in the Earth's atmosphere, were changing into tau neutrinos before they reached the detector (Totsuka et al 1998). Then in Canada, the Sudbury Neutrino Observatory (SNO) finally broke a thirty year drought, with conclusive evidence of neutrino oscillations (Ahmad 2002). Interestingly, it wasn't until 2010 that the theorised conversion of muon-neutrinos into tau-neutrinos was actually observed by scientists with the OPERA experiment at CERN in Italy (CERNweb).

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