3 Solar neutrino physics

Nuclear processes in stellar cores produce large numbers of neutrinos of energy ~ 1 MeV. The feeble interaction of neutrinos with matter ensures that they exit the core and star with near 100% transmission. This makes neutrinos a unique probe of stellar astrophysics. Here we focus on MS stars, specifically the sun. The underlying physics, the story of solar neutrino detection, and the "solar neutrino problem," and its resolution are briefly discussed in this lecture.

3.1 Neutrinos are elementary particles

We discussed neutrinos earlier in our brief introduction to the elementary particles. Because the neutrinos couple only to the weak force, they are very difficult to detect directly. It is not so much that the weak force has a small intrinsic strength — the coupling constant is actually slightly larger than the electromagnetic coupling. The weak force, however, has a very short range. So while at an energy ~ 100 GeV, the strength is comparable to EM, at low energy, where the deBroglie wavelength is large compared to the force range, the effective strength is tiny. The range helps us understand why the primary neutrino cross sections obey $\sigma \propto E^2$ for $E \ll 100$ GeV, which is the range of interest for us.

A neutrino interaction was not directly observed until 1956 by Reines and Cowan. However, their existence was inferred and expected beforehand. In 1932 Pauli predicted their existence. He based this on the observed energy spectra of electrons or positrons from beta decay processes such as

$$^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + e^{+}[+\nu_e] \; .$$

If the final state really consisted only of 2 bodies, then E_e is a constant, depending only on the masses involved. Instead, a continuous distribution was observed for E_e. Pauli reasoned that either energy is not conserved in such decays (!) or an undetected particle was present in the final state. . . the neutrino.

There are 3 species of neutrinos, ν_e, ν_μ and ν_τ, one in each of the 3 "generations" of elementary particles. However, with notable exceptions, most processes we consider in astrophysics involve only generation 1 (this is the lightest), so we mostly encounter ν_e (and $\bar{\nu_e}$). Neutrinos were originally assumed to be massless. However we now know their masses to be finite, in part due to the solar neutrinos discussed below. Their mass values are not known, but they are small, likely to have $m_\nu \ll 1$ eV/c^2.

3.2 Predictions for neutrino production

A simple calculation provides a good estimate of the expected flux of solar neutrinos at the earth. By first approximation, the PPI chain provides the solar power we observe on earth. As discussed in lectures 4 and 5, every iteration of this sequence results in 2 ν_e and 27 MeV of kinetic energy, which we observe eventually as luminosity. This luminosity corresponds to a power of 137 mW/cm^2 = 8.53×10^{11} MeV/(cm^2 s. Hence, we expect the neutrino flux at earth to be

$$8.53 \times 10^{11}/(27/2) = 6.4 \times 10^{10}\ {\nu_e}'\mathrm{s}/(\mathrm{cm}^2\, s)\ .$$

Figure 9 is the state of the art prediction of the overall solar neutrino flux at earth from Bahcall, *et al.* The estimate above is indeed rather close to the calculated PP flux. The peaking of the curves near the maximum energy is due to the parity-violating nature of the weak interaction. We note that although the PP neutrinos dominate the flux, their energy is limited to below ≈ 0.4 MeV. The neutrinos from ${}^8_5B$ decay on the other hand extend to about 15 MeV.

3.3 Solar neutrino detection

Detection of neutrinos in general is difficult. In high-energy (*i.e.* elementary particle) physics, neutrino beams can be produced and used as a very incisive probe of the weak force. However, this is only practical because the interaction probability (cross section) inreases rapidly with energy, as noted earlier. Hence, for a neutrino in a beam with energy ∼ 100 GeV, the interaction rate is large enough so that an experiment at Fermilab called NuTeV was able to collect a few million neutrino events over about a year of data collection. (These were the pictures I showed in class of a huge "splat" of energy in the center of large quantity of iron.) The experimentalist hoping to measure solar neutrinos does not have the advantage of such high energy, although the flux of neutrinos is large, as seen above.

Figure 10 summarizes the principal detectors used to measure solar neutrinos over the last few decades. The field was pioneered by R. Davis, who

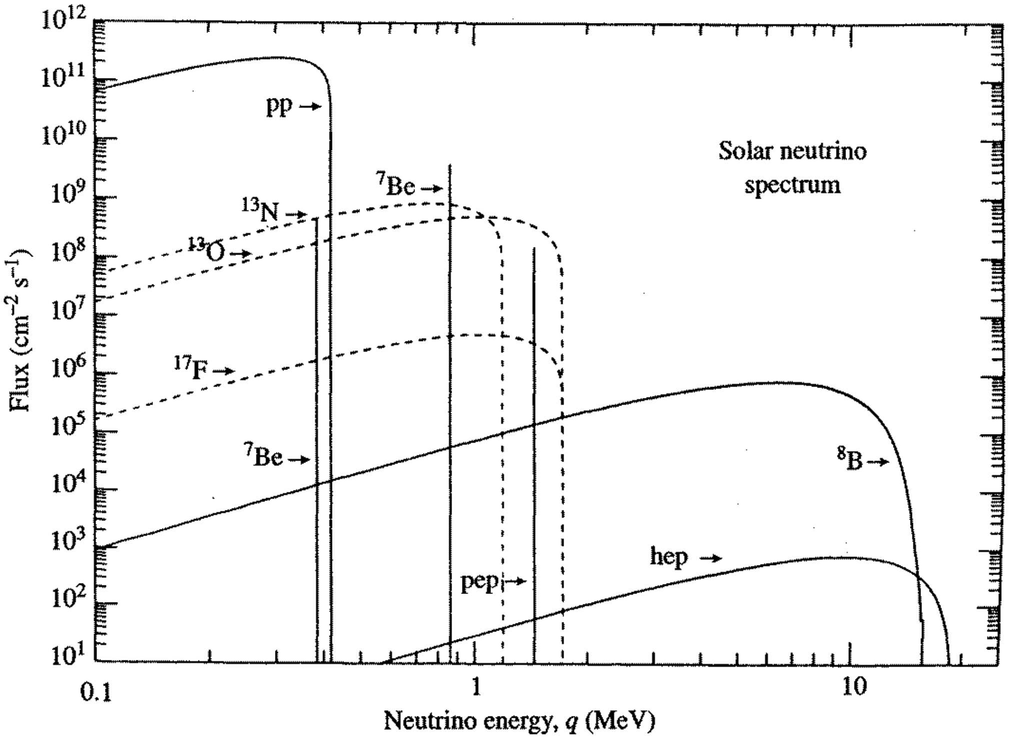
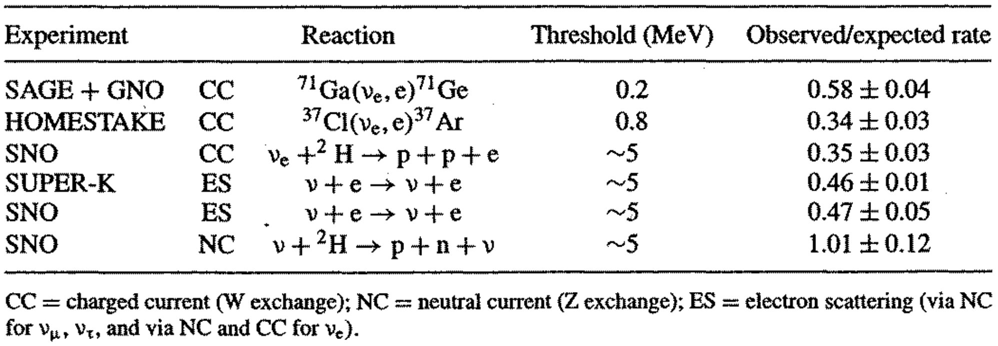


Figure 9: Predicted solar neutrino spectra – the flux at earth as a function of neutrino energy. (From Bahcall.)

came up with a viable detector consisting of a large vat of cleaning fluid deep underground (in a mine at Homestake, SD). The experiment is sensitive to neutrinos in the reaction

$$\nu_e + {}^{37}\mathrm{Cl} \to e + {}^{37}\mathrm{Ar} \ .$$

The resulting argon gas bubbles out and is extracted. Since this isotope of argon is unstable, its quantity is determined by measuring the decay curve. All solar neutrino experiments are deep underground, so that cosmic ray particles are filtered out by the overburden. The Davis experiment ran for about two decades with a measured flux which on average was $(34 \pm 3)\%$ of the predicted flux before the result was confirmed by other experiments. In the meantime, there was a great deal of debate about the result. Davis's experiment was primarily sensitive to ^8B neutrinos, since its threshold is above the PP neutrinos. Could the solar theory be trusted for non-PP sequences, where there are such large temperature dependences (see lecture 5)? The discrepancy between theory and experiment was known as the *solar neutrino problem.*



Experiment		Reaction	Threshold (MeV)	Observed/expected rate
SAGE + GNO	CC	$^{71}\mathrm{Ga}(\nu_e, e)^{71}\mathrm{Ge}$	0.2	0.58 ± 0.04
HOMESTAKE	CC	$^{37}\mathrm{Cl}(\nu_e, e)^{37}\mathrm{Ar}$	0.8	0.34 ± 0.03
SNO	CC	$\nu_e + {}^2\mathrm{H} \to p + p + e$	~5	0.35 ± 0.03
SUPER-K	ES	$\nu + e \to \nu + e$	~5	0.46 ± 0.01
SNO	ES	$\nu + e \to \nu + e$	~5	0.47 ± 0.05
SNO	NC	$\nu + {}^2\mathrm{H} \to p + n + \nu$	~5	1.01 ± 0.12

CC = charged current (W exchange); NC = neutral current (Z exchange); ES = electron scattering (via NC for ν_μ, ν_τ, and via NC and CC for ν_e).

Figure 10: Main solar neutrino detectors and measured fluxes. (From Perkins.)

The next big breakthrough was the gallium experiments, SAGE and GNO. The technique was similar to the Davis experiment, except using gallium as the target, which has a threshold of only 0.2 MeV in the process indicated in Fig. 10. These experiments were sensitive to the PP neutrinos, and their detected flux was roughly half that expected by theory. Meanwhile, the Super-K experiment in Japan had also confirmed the missing high-energy flux using a technique which allowed them to actually image the direction of the neutrinos, confirming their solar origin. The detectors using water as a neutrino target rely on the following principle. The solar neutrinos collide with an atomic electron, sending it out into the water as a free particle with a speed close to c. This is faster than the speed of light in the water, which has speed c/n, where n is the index of refraction. This results in a shock-wave phenomenom known as Cherenkov radiation, which can be detected by sensitive light detectors (photo-multiplier tubes) installed on the periphery of the water tank.

The "problem" was finally resolved a few years ago by the SNO experiment. Recall that we know that there are 3 species of neutrino, ν_e, ν_μ, and ν_τ. The Davis and gallium experiments could only measure the ν_e type. Since only ν_e are produced in the nuclear reactions in the sun, this may not seem to be an issue. However, we note that the Super-K measurements were slightly sensitive to the other two types, and they measured a higher rate. The SNO breakthrough was that its detection target material is *heavy water*, that is H_2O where the H is largely deuterium, ${}^2_1H$. As we said in lecture 4, the deuteron is very weakly bound. Hence a neutrino of a few MeV energy can disassociate the deuteron. The resulting charged proton can be observed by the Cherenkov technique. This process,

$$\nu_x + {}^2\mathrm{H} \rightarrow p + n + \nu_x \ ,$$

is equally likely for any of the 3 neutrino species, x.

The SNO result for this reaction is consistent with the predicted solar flux. This means that the "problem" was not a problem with the solar theory, but rather indicated a new property of the neutrinos themselves, as discussed briefly below. The ν_e type produced in the solar core were turning into the other species with some probability on their journey to the earth. The other detectors only saw the remaining ν_e's, but SNO saw them all. Hence, SNO not only confirmed the origin of the "problem," but also confirmed that the solar theory indeed predicted the correct neutrino flux. Davis shared the 2002 Nobel Prize in physics.

3.4 Neutrino oscillations and mass

To illustrate the point, we discuss only two neutrino species. The generalization to three is qualitatively the same, but is more complicated. Let the neutrino species have small, but finite masses, with values (eigenstates) m_1 and m_2. The quantum state for m_1 will in general be a linear combination of ν_e and ν_μ. The state begins as ν_e, as determined by the weak interaction process in the solar core. Now, quantum mechanics requires that the mixed state evolve in time according to

$$\psi(t) = \psi(0)e^{-\imath(\Delta E)\,t/\hbar} \ ,$$

where ΔE is the energy difference of the states. Relating this to the mass eigenstates and t to the distance travelled, the probability for transition from one type of neutrino to the other, called *neutrino oscillation*, over a distance L (in km) in vacuum becomes:

$$P_{1\to 2} = P_{2\to 1} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\,L/E\right) \tag{15}$$

at an energy E (in GeV), and $\Delta m^2 = m_2^2 - m_1^2$ is in eV^2/c^2. The parameter θ determines the linear combination $\psi_1 = \cos\theta\,\psi_e + \sin\theta\,\psi_\mu$ and is called the mixing parameter. One additional detail: While the neutrinos do not get significantly absorbed by the sun on their outward trek, there is an interesting resonance effect where the neutrino mass difference matches the ambient mass density. The interaction is analogous to light passing through transparent material with index of refraction > 1. The effect is called MSW enhanced oscillations, and can easily result in maximal mixing of the neutrino states, *i.e.* $\tan\theta \approx 1$. In this case we would also expect the ratio of ν_e to total flux at earth to be $\approx \frac{1}{2}$, with some energy dependence from Equation 15. The data are consistent with both of these predictions.

Hence, the resolution of the solar neutrino problem requires finite neutrino masses. This effect has also been seen in other types of neutrino experiments, so it is known that all 3 types mix with each other. While only Δm^2 is directly measured, the implications from all the data are quite strong that the individual masses are very small, $m \ll 1$ eV/c^2. If this is indeed the case, as we shall see later, this makes neutrino mass irrelevant for cosmology.