Lecture 8 : Stellar Energy Sources and the Solar Neutrino Problem

8.1 MASS DEFECT

In lecture 3 we looked at several potential energy sources for the Sun, and found expressions for the free-fall time, the Kelvin-Helmholtz time (energy release via gravitational contraction) and the Einstein time (energy release via nuclear burning). So far, in all our discussions of stellar interiors, we have been able to derive a range of stellar properties without considering at all how the energy is released.

It was not until the 1930's through to the 1950's that this issue was resolved, that the energy is a result of "fusion" or "nuclear burning".

The masses of the some of the important elements are shown in table 8.1. For each element, the **mass defect** is shown in the 4th column. This is the difference between the atomic mass obtained by combining an appropriate number of H atoms and the measured mass of the element. This mass defect is the source of nuclear energy. For Hydrogen burning into Helium, a mass defect of 0.0288 amu yields for the Sun of order 2×10^{52} erg over the Sun's lifetime (circa 4.5×10^9 years). This is about a factor of 100 times more energy than has been released over this time by the Sun, based on its present luminosity.

The idea that the source of energy is gravitational contraction can be revived, by considering how small the Sun would have to shrink to in order to release gravitational energy $E_{\rm grav}$ of similar order to the nuclear energy. We require

$$E_{\rm grav} = \frac{GM^2}{R} > 2 \times 10^{52} \text{ erg} \quad (8.1)$$

Problem 8.1 Show that the Sun would have to shrink to a density of order 5×10^{11} g cm^{-3} in order for gravitational energy release to be competitive with its energy release by nuclear burning. What would the radius of the Sun be? These kinds of densities are actually obtained for **neutron stars**.

8.2 TUNNELING

At a temperature of order $T = 15 \times 10^6$ K, the typical thermal energy of the protons is (i.e. kinetic energy) is

$$\text{KE} = \frac{3}{2}kT = 2 \times 10^{-9}\text{erg} \approx 1\text{keV} \quad (8.2)$$

On the other hand, the energy of the Coulomb barrier is of order

$$\frac{e^2}{r_0} \quad (8.3)$$

A	Isotope	$(Am_H)/m$	$\Delta m/(Am_H)$
1	H^1	1.000000	
4	He^4	4.032688	0.71%
12	C^{12}	12.098064	0.78%
16	O^{16}	16.130752	0.81%
20	Ne^{20}	20.163440	0.82%
56	Fe^{56}	56.457632	0.89%

where $r_0 \approx 10^{-13}$ cm is the radius at which the Coulomb potential is of the same strength as the nuclear potential (the Coulomb force is repulsive while the nuclear force is attractive).

The energy of the **coulomb barrier** is of order

$$E_{\rm Coul} = \frac{e^2}{r_0} = 2 \times 10^{-6} \approx 1\text{MeV} \quad (8.4)$$

This is about a factor of 1000 more energy than the typical proton kinetic energy.

Problem 8.2 If the velocities of the protons in the Sun are Maxwellian (see Lecure 6), what fraction of the protons have a kinetic energy 1000 times greater than average? Are there enough protons in the Sun that one could expect that even 1 proton has such an energy?

Problem 8.2 shows that the number of protons with the necessary energy to penetrate this barrier is essentially zero. The penetration takes place by a process called **tunneling**, in which particles with even low kinetic energy can pass through a barrier due to quantum-mechanical effects.

An example of this process can be seen in radioactive decay. When $_{84}Po^{212}$ decays, emitting an alpha particle, the energy of the particle is about 9 MeV, whereas the energy of the Coulomb barrier around the nucleus is about 30 MeV. The alpha particle, when it is produced, has a spatial probability function, part of which lies outside the barrier. This leads to a finite quantum-mechanical probability that the particle can appear outside the barrier and then escape. The process of nuclear fusion is essentially the reverse of this procedure.

Penetrating the Coulomb barrier still does not necessarily lead to fusion. For example, the reaction of two protons is quite unlikely because there is no stable Helium nucleus containing just two protons. Instead, the least massive, stable configuration is deuteron, containing a proton and a neutron. In order to produce this, one of the protons must decay into a neutron and a positron while it is within the Coulomb barrier. This is a very unlikely process.

The height of the Coulomb barrier is proportional to the number of protons in the two species which undergo fusion,

Z_1 and Z_2. For this reason, burning of elements above Hydrogen takes progressively higher temperatures in order to proceed. Since the mass of the star sets a limit to the maximum temperature it is capable of sustaining in its core, low mass stars are only able to burn through the lower atomic mass elements, while high mass stars are able to reach all the way to Fe, beyond which the mass defect becomes negative and burning requires energy input rather than producing energy.

There are two major reaction paths which are suppliers of energy in the Sun. These are the proton-proton chain (p-p) and the CN-cycle.

8.3 PROTON-PROTON CHAIN

The p-p chain begins, as described above, by two protons reacting to form a deuteron, D^2. At low temperatures (less than about 14 $\times 10^6$ K), we have the following sequence (termed ppI)
ppI:

p + p	$\rightarrow$ $D^2 + e^+ + \nu_e$	(1.4×10^{10} yr)
p + D	$\rightarrow$ $He^3 + \gamma$	(6 sec)

where the reaction times, typical for the solar core, are show in brackets. For temperatures below about 10^7 K this reaction terminates with the production of He^3. At higher temperatures, an aditional reaction takes place:

$$He^3 + He^3 \rightarrow He^4 + p + p \qquad (10^6 \text{ yr})$$

Note that ν indicates neutrino emission and γ a photon. There are two further routes which can be taken:
ppII:

$He^3 + He^4$	$\rightarrow$ $Be^7 + \gamma$
$Be^7 + e^-$	$\rightarrow$ $Li^7 + \nu$
$Li^7 + p$	$\rightarrow$ $He^4 + He^4$

and
ppIII:

$Be^7 + p$	$\rightarrow$ $B^8 + \gamma$
B^8	$\rightarrow$ $Be^8 + e^+ + \nu$
Be^8	$\rightarrow$ $He^4 + He^4$

The driving factor which determines which of these routes is taken is the $He^3 + He^3$ reaction in the first case and the $He^3 + He^4$ reaction in the second case. Above 14×10^7 K, He^3 reacts preferentially with He^4. This process also depends on the availability of He^4, so it also depends on a supply of He^4 being built up in the stellar core.

The p-p processes release different amounts of energy: for ppI it is 26.2 MeV, for ppIII it is 19.27 MeV. Note however that the energy production rate is controlled by the slowest step, i.e. the production of deuterium, in all p-p chains.

In all the chains, a fraction of the energy produced is released in neutrinos, which have an exceedingly low cross-section ($\sigma = 10^{-44}$ cm^{-2}) with matter and can escape freely from the Sun. For ppI, the fractional energy release is 1.9%; for ppII it is 3.9 %, while for ppIII it is 27.3%. This last chain produces high energy neutrinos, of the type which can be detected on the Earth using specially built detectors, and is a crucial test of the idea that nuclear reactions power the Sun.

There is a significant difference between the amount of neutrinos detected and the amount predicted of a factor of about two. This issue is called the "Solar Neutrino Problem". The problem was first noticed in the 1960's, and has remained a major problem in astrophysics for more than 30 years. There are a number of solutions proposed. Either the neutrino has mass, meaning that neutrinos could change types on their way from the Sun to the Earth. The second solution is much more mundane, and involves adjusting the temperature, reaction rates, energy production rates or other internal parameters of our model of the Sun. However, the European Space Agency satellite SOHO has shown, from measuring oscillations in the Sun, that our models of the Solar interior are extremely good. Even more recently (1999-2000), the latest generation of solar neutrino detectors indicte that the neutrino may indeed be able to change type, so that the solution probably involves new physics.

8.4 CN-CYCLE

Resonance reactions occur when the kinetic energy of a nucleon is compatible with the excited state of the nucleus of the capture product, leading to much higher reaction rates. At higher temperatures than the pp chain, this can lead to the fusion of relatively high atomic number nuclei.

$C^{12} + p$	$\rightarrow$ $N^{13} + \gamma$	(10^6 years)
N^{13}	$\rightarrow$ $C^{13} + e^+ + \nu$	(14 min)
$C^{13} + p$	$\rightarrow$ $N^{14} + \gamma$	(3×10^3 years)
$N^{14} + p$	$\rightarrow$ $O^{15} + \gamma$	(3×10^8 years)
O^{15}	$\rightarrow$ $N^{15} + e^+ + \nu$	(82 sec)
$N^{15} + p$	$\rightarrow$ $C^{12} + He^4$	(10^4 years)

The reaction times are again shown for conditions in the solar center, $T = 14 \times 10^6$ K and $\rho = 100$ g cm^{-3}. The overall effect of this reaction is

$$4H^1 \rightarrow He^4$$

In other words, the amounts of C,N and O are conserved in the cycle, and together they make the process possible.

The pp-chain is governed by the very slow rate of the first reaction, while the CN cycle is governed by the amount of C^{12} available. The CN-cycle requires higher temperatures than the pp-chain, because a higher Coulomb potential is involved. It turns out that it is more important on the upper main sequence (stars more massive than the Sun) while the pp-chain is more important on the lower main sequence (less massive than the Sun).

There is another version of the CN-cycle:

$N^{15} + p$	$\rightarrow$ $O^{16} + \gamma$
$O^{16} + p$	$\rightarrow$ $F^{17} + \gamma$
F^{17}	$\rightarrow$ $O^{17} + e^+ + \nu$
$O^{17} + p$	$\rightarrow$ $N^{14} + He^4$

This cycle is very weak, but can change the isotopic ratios of Oxygen.

8.5 TRIPLE ALPHA REACTION

The next reaction considered involves 3 helium nuclei burning to produce carbon

$$3He^4 \quad \rightarrow \; C^{12} + 2\gamma$$

The path taken is

$$\begin{aligned} He^4 + He^4 &\rightarrow \; Be^8 + \gamma \\ Be^8 + He^4 &\rightarrow \; C^{12} + \gamma \end{aligned}$$

while the reaction yields 7.3 eV, the first step is endothermic (requiring 95 keV to proceed), so that the 3rd alpha particle needs to collide practically immediately with the product of the first reaction, i.e. the reaction is essentially a triple collision.

The reaction takes place around $T = 10^8$ K. At this temperature the kinetic energy of the particles is of order 12 keV, whereas about 95 keV is required in the initial step. This is a similar situation to the formation of the strongest Hydrogen lines in stellar atmospheres at 10,000 K, despite the fact that the thermal kinetic energy is about 1 eV, much less than the ionisation energy (13.6 eV).

The reaction rate is tremendously sensitive to temperature:

$$\epsilon_{3\alpha} \propto \rho^2 T^{30}. \tag{8.5}$$

He can also be burnt via the reaction

$$C^{12} + He^4 \; \rightarrow \; O^{16} + \gamma$$

As a result of these two reactions, the most abundant elements after the completion of He burning are C and O, and so they are the next interesting elements to burn.

8.6 CARBON AND OXYGEN BURNING AND BEYOND

Carbon can be used as an energy source above temperatures of circa 6×10^8 K. The reaction starts with two C^{12}'s and there are quite a number of possible products, important ones being Na^{23} + p; Ne^{20} + He^4; Mg^{23} + n and $Mg^{24} + \gamma$.

Oxygen can then be burnt. The reaction starts with two O^{16}'s and yields, similarly to Carbon, a range of outcomes; $S^{32} + \gamma$; P^{31} + p; S^{31} + n; Si^{28} + He^4 and Mg^{24} + $2He^4$.

The problem with burning by continuing the processes described above is that the temperatures required are so high, of order 3×10^9 K, that the nuclei **photodisintegrate**. As a result, beyond Carbon and Oxygen a quite different mechanism is used, involving the nuclear capture of protons and neutrons.

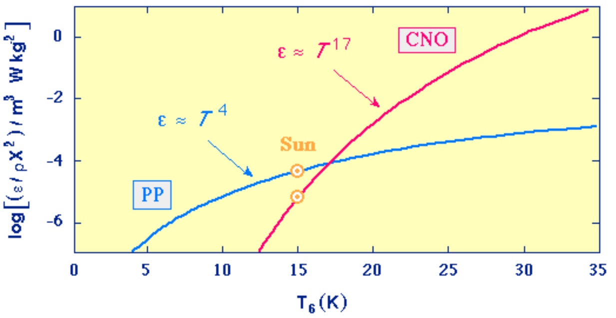

Figure 8.1. Energy generation due to the pp and CN processes as a function of temperature T. Hot (high mass) stars rely on the CNO process, while cool (low mass) stars use the pp-process. http://csep10.phys.utk.edu/astr162/lect/energy/cno-pp.html

8.7 COMPARISON OF MECHANISMS

Table 8.1 shows the relative amounts of energy that can be gained for various species. In the fusion of $4H^1 \rightarrow He^4$, about 26.2 MeV is gained using the pp-chain and about 25.0 MeV using the CNO-cycle. Burning Helium in the triple-alpha process is not nearly so efficient, since the reaction $3He^4 \rightarrow C^{12}$ only yields 7.3 MeV in total, or just 2.4 MeV per He^4. The consequence of this is that stars can burn Hydrogen about 10 times longer than they can burn Helium.

For M type stars, the pp-process completely dominates the energy generation. For the Sun, the pp-process is still much more important than the CNO-cycle, although for detailed calculations of the solar interior the CNO-cycle cannot be ignored. For a star like Sirius A, an A0V (V means it is on the main sequence) with an effective temperature of about 10,000 K, the CNO cycle is more important than pp (see figure 8.1).

The triple-alpha process is not important in main sequence stars like the Sun, but becomes very important after the pp energy source is exhausted. At this stage, the star's core shrinks and becomes hot enough to burn Helium. At the same time the outer layers expand and the star becomes a red giant.

8.8 THE SOLAR NEUTRINO PROBLEM

We have now looked at the energy sources in stars: the p-p chain, the CNO cycle and the triple-α process. The most important of these in the Sun (and cool stars in general) is the p-p chain
p-p chain:

$$4\,{}^1H \quad \rightarrow {}^4He + 2e^+ + 2\,\nu_e + \text{energy}$$

The reaction produces two "electron" neutrinos. Neutrinos are sub atomic particles which travel at (or very close to) the speed of light, with very low interaction with matter. The optical depth of the Sun for a typical neutrino is very low, about 20 orders of magnitude lower than for a photon, meaning that most neutrinos escape the Sun immedeatly after being produced, whereas the energy released in photon form takes of order 10^6 years to escape.

According to the standard prediction of nuclear burning

Table 8.1. Production of Solar Neutrinos

Reaction	Energy (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	0.0 to 0.4
$p + e^- + p \rightarrow {}^2H + \nu_e$	1.4
$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$	0.86, 0.38
${}^8B \rightarrow {}^8Be + e^+ + \nu_e$	0.0 to 15

in the Solar core, the number of neutrinos being produced per second and the number passing through the Earth can be computed. At the Earth, the flux is about 10^{11} per second per square centimeter.

In 1946, Bruno Pontecorvo suggested that Chlorine could be used to detect these neutrinos, providing a means of testing the theory of nuclear burning of Hydrogen into Helium. The suggestion yielded first experimental results in the mid-1960's, when Ray Davis and John Bahcall set up a tank of 100,000 gallons of cleaning fluid (which is composed mostly of Cl) in an old mine. Neutrinos can interact with Cl to produce, very occasionally, a radioactive isotope of Argon (Ar). Each week, a few atoms of Ar were produced, and had to be found and counted in the olympic swimming pool sized tank of fluid!

Davis and Bahcall found about a factor of three less neutrinos than the models predicted. To predict the result within a factor of three was and still is a splendid acheivement, and provided the first direct evidence for nuclear burning. However, as the years passed and the statistics of detected neutrinos built up, the factor of three discrepency remained. It seemed that something was wrong either with the models of the Sun, or our understanding of neutrino physics.

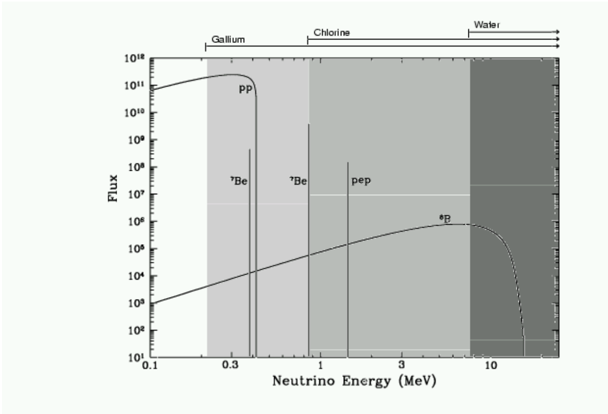

Figure 8.2. Energy distribution of Solar neutrinos as predicted by Solar models. The units of flux for continuum sources (p-p and ^{8}B) are number cm^{-2} sec^{-1} MeV^{-1} at the Earth (i.e. 1 Astronomical Unit from the Sun). For line sources, the unit is number cm^{-2} sec^{-1}. Three ongoing experiments to detect these neutrinos are shown by the grey zones, with the material used in the detector indicated at the top of the plot. Note that the Chlorine experiment *includes* the ^{7}Be line.

8.9 THE SOLAR NEUTRINO SPECTRUM

The p-p chain dominates neutrino production in the Solar core. It produces neutrinos with a range of energies (continuum sources) and with precise energies (line sources). The reactions are shown in Table 1 and illustrated in figure 1.

The basic p-p reaction creates neutrinos with energies less than 0.4 MeV, and it is this reaction which dominates the energy production that eventually emerges as sunlight at the Solar surface. Models of the interior of the Sun are thought to be so well understood that the uncertainty in the predicted flux of p-p neutrinos is only 1%. Approximately 0.2% of the neutrinos are produced by the pep reaction, resulting in a "line" of fixed energy (1.4 MeV). The next most important source results in the ^{7}Be line at 0.86 MeV, and the energy produced by the parent reaction accounts for about 15% of the Solar luminosity. The uncertainty in the flux of ^{7}Be neutrinos is about 10%. The flux of ^{8}B neutrinos is very small, about 1 per 10,000 p-p neutrinos. However, the have a high energy, or order 10 MeV, and dominate the first experiment designed to detect Solar neutrinos (using Chlorine). These neutrinos dominate water based detectors (these search for Cherenkov light), but unfortunately the error in the flux of the ^{8}B neutrinos is the largest of all the predicted fluxes, of order 20%.

A convenient unit for measuring Solar neutrinos is the SNU, or Solar Neutrino Unit, which is defined as 10^{-36} interactions per target atom per second. The original estimate of the Solar neutrino flux by Bahcall and Davis was 7.5 ± 1.0 SNU; today, after almost 40 years of refinements to the Standard model of the Sun as a result of ork by thousands of scientists, the best estimate is 7.7 ± 1.1 SNU, so the value has hardly changed. How can this be so accurately predicted, given that the production of neutrinos depends so heavily on the energy production at the Solar core, which we otherwise have no way of testing?

The three main ingredients are 1) the input physical data for processes at the Solar core, 2) the Solar luminosity and 3) the oscillation frequencies of the Sun.

The physical data for the nuclear burning processes represent decades of work in many laboratories. Accurate opacities, forms for the equation of state, the cross-sections of the reactions, the abundances of elements from analysis of the Solar spectrum (at the Solar surface) and laboratory data on nuclear reaction rates have all been extensively studied and importantly, have *well quantified uncertainties*.

The Solar luminosity is known experimentally to an accuracy of about 0.4%, Models of the Sun are strongly constrained because they must yield this luminosity at the surface, and this also strongly constrains the calculated neutrino fluxes.

Finally, the discovery that the Sun oscillates with a a huge range of frequencies, and their subsequent measurement, has confirmed with spectacular success models of the Sun's structure. More on this in a later lecture.

Taken together, astrophysicists think they understand the Sun so well that the uncertainty in the flux of neutrinos is only $pm15\%$.

8.10 CHLORINE, GALIUM AND WATER BASED DETECTORS

The obvious way forward in understanding the "Solar neutrino problem", after its discovery through the Chlorine based experiment, was to build new detectors. For example, from figure 8.1, one can see that the p-p neutrinos dominate the energy output, but that Chlorine detects the much fewer neutrinos produced by one of the ^{7}Be lines.

In 1986, Koshiba, Totsuka, Beier and Mann refitted a huge water tank, originally designed to test the stability of matter, to detect neutrinos from the ^{8}B continuum. This experiment, called Kamiokande, confirmed the factor of three issing in the neutrino flux, and further confirmed that the neutrinos were coming from the Sun (it was sensitive to the direction of the neutrinos path in space).

Subsequent experiments (SAGE, GALLEX, GNO and Super-Kamiokande) have further verified that part of the Solar neutrinos are missing. Interestingly, the energies of the detected neutrinos do match the theoretical predictions. What is going on?

8.10.1 Chlorine based experiments

The first experiment performed, with Cl, detected electron neutrinos ν_e with energies above 0.81 MeV. The experiment has been running for over 30 years, and has yielded a flux of 2.6 ± 0.2 SNU, a factor of 3 less than the predicted flux. The Cl detector is dominated by high energy ^{8}B and some ^{7}Be neutrinos, while SNO and pep neutrinos contribute about 15% of the total signal. Because the discrepency between the expected and measured rates is different for the dfferent detectors, what used to be termed the "Solar neutrino problem" for Cl is now termed the "first Solar neutrino problem".

8.10.2 Water based experiments

The experiments using water (Kamiokande and Super-Kamiokande) are sensitive to higher energy neutrinos only (see figure 8.1) of 7.5 MeV and 6.5 MeV respectively. The experiment measure the Cherenkov radiation emitted during neutrino-electron scattering (ν + e $\rightarrow \nu'$ + e$'$). The direction and energy of the neutrinos can be reconstructed from the direction and amount of Cherenkov radiation produced.

The water experiments are dominated by the same processes which produce neutrinos as in the Chlorine experiments, i.e. beta decay of ^{8}B, and is thus an independent check. The shape of the ^{8}B spectrum turns out to be quite insensitive to Solar physics, meaning that the ratio of detection rates in the Cl and water experiments is well determined. Measuring the flux in the water experiments means that the fractional rate in the Cl experiment can be predicted: it turns out to be 2.8 ± 0.1 SNU, whereas the measured rate in Cl is 2.6 ± 0.2 SNU. All of this is to say that there is a small difference between the detected rates in the two experiments — the Cl experiment gives a discrepency of about 3 in the rate, while the discrepency is about 2 for the water experiments.

The discrepency between the H_2O and Cl experiments is termed the "second Solar neutrino problem". A possible solution is that the computed spectrum of neutrinos from ^{8}B decay is not correct; i.e. the standard model in physics of the neutrino is not correct. More on this later.

8.10.3 Gallium based experiments

Two experiments are currently running using Ga as the detector, GALLEX and SAGE. Ga is very interesting because it is sensitive to the p-p and pep neutrinos — which is after all where most of the neutrinos are being produced.

The experiments taken together give a flux of 73 ± 5 SNU, (they pretty well agree with each other within experimental error). As seen in figure 8.2, the total expected flux in neutrinos detectible by Ga is 129 ± 7 SNU. Of this, 72 SNU is predicted to come from the p-p and pep reactions: i.e. the Ga experiments could be completely explained by these reactions only. The remaining contribution to the Ga flux is from ^{8}B neutrinos (about 12 SNU) and ^{7}Be (about 34 SNU). The observed rate is about 60% of the predicted rate, so the discrepency is just less than a factor of two.

The discrepency in the Ga experiments is termed the "third Solar neutrino problem". Since Ga is the only experiment which detects p-p neutrinos, the discrepency can be viewed as independent of the other neutrino discrepencies.

8.10.4 What the experiments show

Three detectors have been used to measure the Solar neutrino flux. The experiments show that:

- neutrinos are observed coming from the Sun
- the energies of the Solar neutrinos are in reasonable accordance with theory
- all three experiments show a smaller than expected neutrino flux
- the ratio of expected to predicted fluxes differs amongst the experiments 0.3 for Cl, 0.5 for H_2O and 0.6 for Ga
- the flux should vary slightly throughout the year, i.e. there are small seasonal effects, but the experiments are not yet accurate enough to detect it

All attempts to modify the Solar model to explain the results of the five neutrino experiments have failed; furthermore, the Solar models have no been probed independently through Solar oscillations (Helioseismology) and have been shown to be very accurate. On the other hand, many modifications to the properties of the neutrino, all of which reveal new physics (because they go beyond the standard model), can explain the results of all the experiments.

8.11 NEW PHYSICS?

Neutrinos come in three flavours, or types, e, μ and τ. In the standard electroweak model, they are massless particles and travel at the speed of light. Furthermore, in beta decay or nuclear fusion reactions, the standard model predicts that only electron type neutrinos will be created, ν_e. All the neutrinos produced in the Sun should be of this type. Since there are three neutrino types, it was very interesting when the Cl experiments detected about a factor of three less neutrinos than predicted. Since, this experiment could only detect the electron neutrinos, it raised the possibility that two thirds of the neutrinos were in the other two flavours and hence not

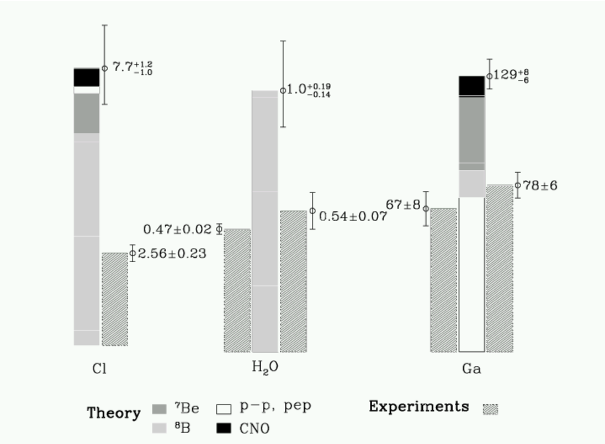

Figure 8.3. Measured neutrino fluxes for experiments using Chlorine, water and Galium. The units are SNU. The shading indicates the sources of neutinos in each predicted flux, either from ^{7}Be, ^{8}B, p-p/pep or the CNO chain. The discrepency between experiment and prediction is clear in each experiment, although the difference is not always the same.

detected. Perhaps the neutrinos change flavours (oscillate) on their way to the Earth?

A number of modifications to the standard model exist which predict that neutrinos have mass, and as a consequence can exhibit oscillations. Two of these are vacuum oscillations (suggested by Gribov and Pontecorvo) and resonant matter oscillations (Mikheyev, Smirnov and Wolfenstein, or MSW). In the vacuum oscillation thery, neutrinos are able to change state as an intrinsic property. In the resonant matter theory, the state change is induced by passing through matter.

Neutrinos are produced by particles in the Earth's atmosphere via the collision of high energy cosmic rays. In 1998, the Super-Kamiokande experiment announced results which show that such neutrinos undergo oscillations.

At present there is only one way to test directly any of the new theories for Solar neutrinos, via the recoil energy spectrum of the electrons in the Super-Kamiokande experiment. However, this depends on another neutrino production mechanism than we have considered so far, termed hep, which is ^{3}He + p $\rightarrow$ ^{4}He + e$^+$ + ν_e. Unfortunately the predicted flux for this reaction cannot yet be computed with confidence because of fundamental physical uncertainties, and does not promise a solution to the question of neutrino oscillations. A whole new generation of neutrino detectors which can measure the neutrino energy spectrum is needed to resolve this issue.

Problem 8.1 A number of Solar neutrino detectors are running
at present. A list of them and their websites is available at http://www.sns.ias.edu/~jnb/SNexperiments/experiments.html. Choose one experiment, and write a few pages describing it. Some issues you could look at are

- what material is used in the detector?
- what reaction takes place with neutrinos in the detector?
- how much material is required in the detector to get a useful measurement of the neutrino flux?
- which of the reactions in the solar core is the detector sensitive to?
- does the experiment measure the energy and direction of the incoming neutrino?
- how many neutrinos come from other sources than the Sun?
- how long will the experiment run, what did it cost, where is it situated physically in the Earth and why?
- something else interesting I didn't suggest here!

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