The Solar Neutrino Problem

There are 6 major and 2 minor neutrino producing reactions in the sun. The major reactions are

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \longrightarrow {}^{2}\mathrm{H} + \mathrm{e}^{+} + \nu_e \qquad (\mathrm{PP-I})$$

$$^{7}\mathrm{Be} + \mathrm{e}^{-} \longrightarrow {}^{7}\mathrm{Li} + \nu_e + \gamma \qquad (\mathrm{PP-II})$$

$$^{8}\mathrm{B} \longrightarrow {}^{8}\mathrm{Be} + \mathrm{e}^{+} + \nu_e \qquad (\mathrm{PP-III})$$

$$^{13}\mathrm{N} \longrightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu_e \qquad (\mathrm{CN})$$

$$^{15}\mathrm{O} \longrightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu_e \qquad (\mathrm{CN})$$

$$^{17}\mathrm{F} \longrightarrow {}^{17}\mathrm{O} + \mathrm{e}^{+} + \nu_e \qquad (\mathrm{NO})$$

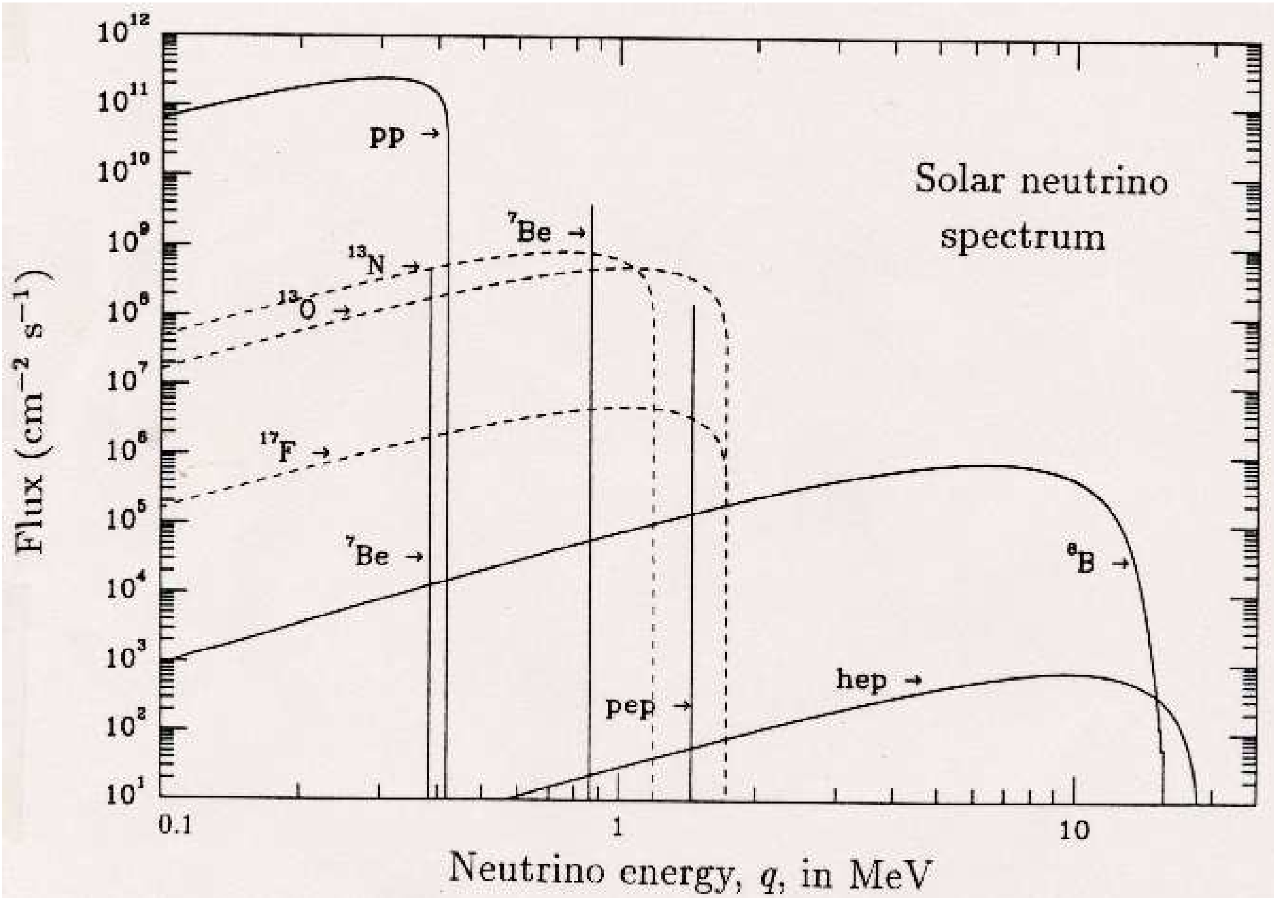
while the much rarer three-body neutrino-producing reactions are

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} + \mathrm{e}^{-} \longrightarrow {}^{2}\mathrm{H} + \nu_e \qquad (\mathrm{PEP})$$

$$^{3}\mathrm{He} + {}^{1}\mathrm{H} + \mathrm{e}^{-} \longrightarrow {}^{4}\mathrm{He} + \nu_e \qquad (\mathrm{HEP})$$

Most of these reactions produce neutrinos with a continuum of energies (which depend on the velocities of the interacting particles). The ^{7}Be reaction, however, takes the ^{7}Li nucleus into one of two excited states and the neutrino is produced when the state decays. The result is neutrino "line" emission, at one of two energies. Similarly, the PEP reaction produces a neutrino emission line.

The rate of these reactions (and the distribution of neutrino energies) depends on the detailed model used for the Sun. When a "standard" solar model is used, the solar neutrino spectrum on the next page is produced.



The energy spectrum of neutrinos produced in the Sun by the standard solar model. The units on the continuum fluxes are number per cm^2 per second per MeV at 1 A.U.; the units on the line fluxes are number per cm^2 per second. The solid lines show the spectra from the pp-chain; CNO neutrinos are the dotted lines.

Reaction	$\langle \epsilon_\nu \rangle$ (MeV)	Energy Range (MeV)	Neutrino Flux at Earth (10^{10} cm^{-2} s^{-1})
^{1}H$(p, \beta^+ \nu)^2$H	0.263	$\epsilon_\nu < 0.420$	6.0 ($\pm 2\%$)
^{7}Be$(\beta^-, \nu_e)^7$Li	0.80	90% at 0.861	
		10% at 0.383	0.47 ($\pm 15\%$)
^{8}B$(\beta^+, \nu)^8$Be*	7.2	$\epsilon_\nu < 15$	5.8×10^{-4} ($\pm 37\%$)
^{13}N$(\beta^+, \nu)^{13}$C	0.710	$\epsilon_\nu < 1.20$	0.06 ($\pm 50\%$)
^{15}O$(\beta^+, \nu)^{15}$N	1.00	$\epsilon_\nu < 1.73$	0.05 ($\pm 58\%$)
^{17}F$(\beta^+, \nu)^{17}$O	0.94	$\epsilon_\nu < 1.74$	5.2×10^{-4} ($\pm 46\%$)
^{1}H$(p\beta^-, \nu_e)^2$H	1.44	$\epsilon_\nu = 1.442$	0.014 ($\pm 5\%$)
^{3}He$(p\beta^-, \nu_e)^4$He	10	$\epsilon_\nu < 18.77$	8×10^{-7}

Most of the data on solar neutrinos comes from 4 experiments, Kamiokande II (Japan), Homestake (US), GALLEX (European) and SAGE (Russian). These use three types of detection schemes:

• **Cerenkov detectors:** The Japanese Kamiokande II experiment uses 3 kilotons of water located in a tank 1 km underground. The tank is painted black, and 20% of its inner surface is covered with high efficiency photomultiplier tubes. High energy neutrinos scatter electrons in the tank, causing the electrons to move at a speed $v > c/n$, where $n = 1.344$, the index of refraction of water. Cerenkov light is then emitted by the electron in a cone with angle

$$\cos\theta = (n \times \beta)^{-1}$$

where $\beta = v/c$. Because the recoil velocity of the electron must be large, only neutrinos with $\epsilon > 5$ MeV can be detected. Thus the experiment is only sensitive to the ^{8}B (and HEP) reactions. Moreover, to avoid contamination from spurious cosmic muons, neutrons, *etc.*, only the central 680 tons of water is useful for counting solar neutrinos. However, the nature of the experiment does allow for time and angular resolution (28° at 10 MeV). [This detector, along with a Cerenkov detector in a salt mine in Ohio, detected the SN 1987A neutrinos.] Note, however, that this Cerenkov detector is triggered about once every two seconds, while the expected rate from solar neutrinos is 0.3 events per day!

• **Chlorine Detectors:** A ^{37}Cl detector has been operational for the past 30 years in the Homestake Gold Mine of Lead, South Dakota. The experiment uses a tank filled with 10^5 gallons (615 tons) of cleaning fluid (C_2Cl_4) and is based on the reaction

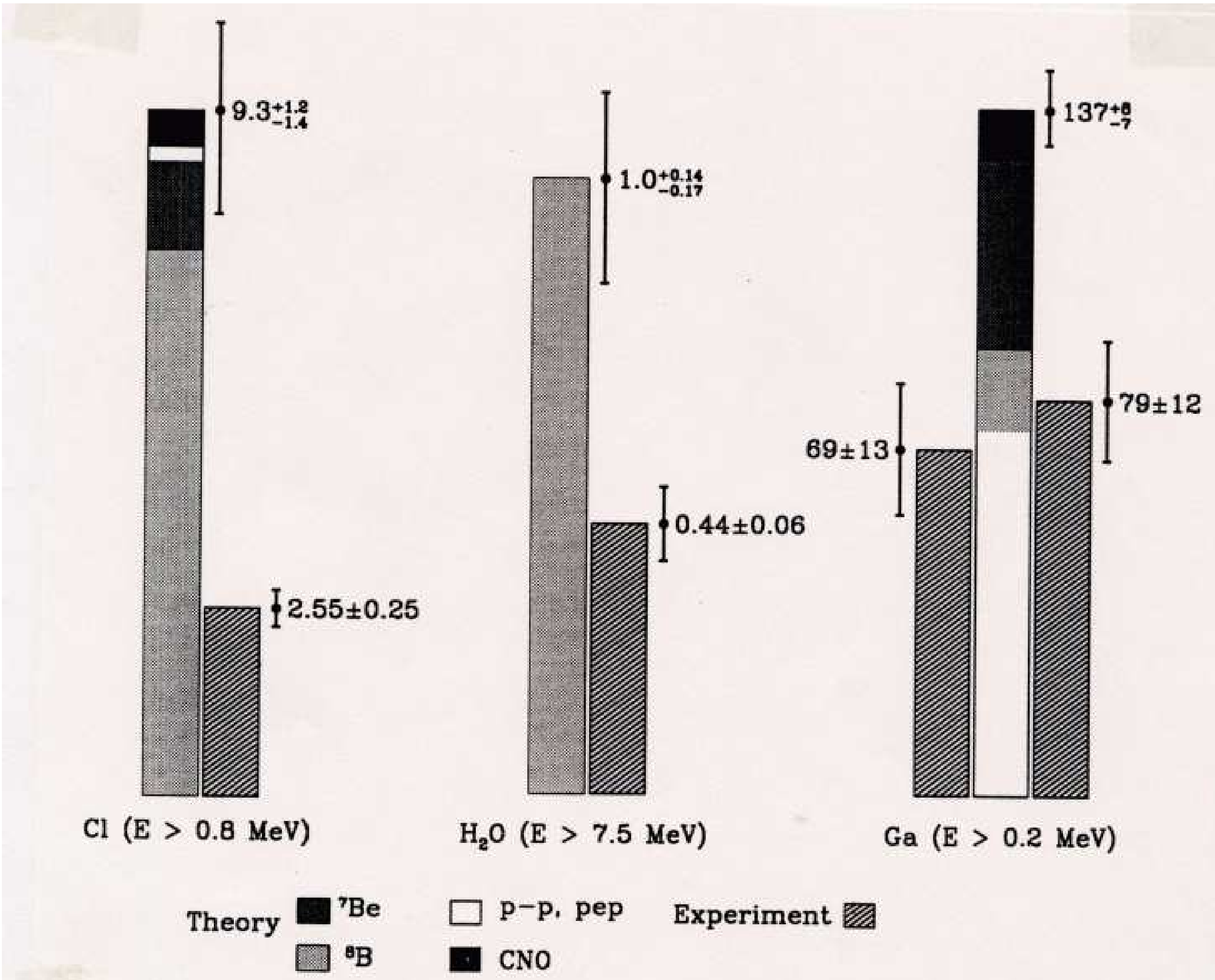
$$^{37}\mathrm{Cl} + \nu_e \longrightarrow {}^{37}\mathrm{Ar} + e^- \qquad (19.1)$$

The threshold for this reaction is 0.814 MeV; thus it is sensitive to all solar neutrinos *except* those from produced by the PP-I reaction. The reaction product (^{37}Ar) is collected by circulating He through the tank (which drags the Argon along with it), trapping the ^{37}Ar in charcoal, and monitoring its radioactive decay (half-life of 35 days). The technique is $\sim 95\%$ efficient. Since 1970, the average production rate of ^{37}Ar has been 0.462 ± 0.04 atoms per day, with a background of 0.08 ± 0.03 atoms per day.

• **Gallium Detectors:** The GALLEX and SAGE experiments use the reaction

$$^{71}\mathrm{Ga} + \nu_e \longrightarrow {}^{71}\mathrm{Ge} + e^- \tag{19.2}$$

which has an energy threshold of 0.2332 MeV. These Gallium detectors are thus unique in that they can detect the low energy PP-I neutrinos. GALLEX consists of 30 tons of gallium in a 105 ton concentrated solution of $GaCl_3$-HCl; the SAGE experiment uses 60 tons of metallic gallium. (This compares to the total rate of Gallium production worldwide in the 1980's of 10 tons per year.) GALLEX extracts $GeCl_4$ by bubbling nitrogen gas through the tank, and chemically separating Ge from Cl using charcoal and $NaBH_4$; SAGE collects Ge by melting the Ga metal (melting temperature 30° C), and mixing it with hydrochloric acid. SAGE has the advantage of being less sensitive to background reactions produced by radioactive impurities and has a smaller volume; its main disadvantage is that new ingredients must be added each time the germanium is separated. Thus the experiment may be susceptible to systematic errors. Both experiments count the ^{71}Ge by creating GeH_4 and monitoring its radioactive decay.



Comparison of the measured and predicted rates for 4 solar neutrino experiments (a decade ago). The standard unit for measuring solar neutrinos is the Solar Neutrino Unit (SNU), where 1 SNU equals 10^{-36} interactions per target atom per second. This unit is therefore depends on the (energy dependent) cross-section of the target particle (typically $\sim 10^{-44}$ cm^{-2}).

NON-STANDARD MODELS

A large number of non-standard solar models have been proposed to explain the neutrino discrepancy. Some ways of doing this are

• *Modifying the Equations of Stellar Energy Transport.* If the temperature gradient in the Sun can be decreased, then the central temperature can be decreased. This will change the rate of nuclear reaction and the amount of high energy neutrinos produced. Methods to decrease the temperature gradient include

- Lowering the internal solar metallicity ($\times 10$)
- Precipitating iron in the core
- Adding turbulent diffusion
- Postulating the existence of WIMPs in the Sun's core.

The first two methods decrease the stellar opacity by reducing the bound-free opacity of metals; the latter two methods modify the equations of energy transport by postulating new ways for the energy to escape.

• *Modifying the Equations of Hydrostatic Equilibrium.* If additional pressure support can be found for the Sun's core, then the central temperature can again be decreased. The two ways of doing this are

- Rapid Core Rotation
- Strong Core Magnetic Field

Both methods add an additional term to the equation of hydrostatic equilibrium, so that

$$\begin{aligned} \frac{dP}{dr} &= -\frac{G\mathcal{M}}{r^2}\rho + \rho\left(\omega\sin\theta\right)\right)^2 r - \frac{1}{8\pi}\frac{dB}{dr} \\ &= -\frac{G\mathcal{M}}{r^2}\rho + \frac{2\rho\omega^2 r}{3} - \frac{1}{8\pi}\frac{dB}{dr} \end{aligned} \tag{19.3}$$

where ω is the core's rotational frequency, θ is the latitudinal coordinate, and B is the magnetic field. To reconcile the models with observations the gas pressure must be modified by $\sim 1\%$, so that

$$\epsilon = \frac{2\omega^2 r^3}{3G\mathcal{M}} \sim 0.01$$

or

$$\beta = \frac{B^2 r^2}{8\pi G\mathcal{M}\rho} \sim 0.01 \tag{19.4}$$

The former equation implies that the core ($\mathcal{M} \sim 0.01\mathcal{M}_\odot$, $r \sim 0.05R_\odot$) must have a rotational period of an hour; the latter implies of field of $\sim 10^9$ Gauss.

• *Modifying the Mean Molecular Weight.* If the mean molecular weight of the core is lower than predicted, then the temperature required to support the core need not be as high. Ways to modify μ include hypothesizing

- Internal Mixing via Rotation
- Internal Mixing via g-mode oscillations
- High Stellar Mass Loss

The last of these three methods actually increases the neutrino flux, since the higher initial mass would imply a more rapid conversion of hydrogen to helium in the past, and thus a higher molecular weight. The first two methods, however, would decrease μ by mixing unprocessed material into the core, either through the effects of stellar rotation or through g-mode pulsations.

• *Adding Additional Energy Sources.* If the Sun had an additional energy source, then the amount of hydrogen fusion occuring in the Sun's core could be decreased without affecting the stellar structure. The other energy source could be

- A Central Black Hole

- Fusion of free quarks, or Q-particles
- CNO burning around a Small Burnt-Out Core

The last of these three suggestions isn't really a new energy source; it just exchanges PP-III neutrinos for CNO neutrinos. Similarly, the Q-particle solution, which hypothesizes that there is another way for hydrogen to fuse (using some unknown particle as a cataylst), does not actually decrease the number of neutrinos, it only redistributes them into energies that may not be detected (*i.e.,* low energy neutrinos). The black hole hypothesis, however, does decrease the fusion rate. If the black hole is accreting at the Eddington limit (a good assumption), and if this accretion is providing some fraction ϵ of the solar luminosity,

$$\epsilon\mathcal{L} = f\dot{M}_{\rm BH}c^2 = \frac{4\pi c G M_{\rm BH}}{\kappa} \tag{19.5}$$

where $f \sim 0.1$ is the efficiency for converting mass accretion to visual luminosity. If $f \sim \epsilon$, then the mass of the black hole today is $M_{\rm BH} = 2.6 \times 10^{-5}\mathcal{M}_\odot$. However, (19.5) implies

$$\frac{d\mathcal{M}_{\rm BH}}{dt} = \frac{4\pi G}{f\kappa c}\mathcal{M}_{\rm BH}$$

giving

$$\mathcal{M}_{\rm BH}(t) = \mathcal{M}_{\rm BH}(0)\; e^{+t/\tau} \quad \text{where} \quad \tau = \frac{f\kappa c}{4\pi G} \tag{19.6}$$

The black hole will therefore e-fold its mass in $\sim 4 \times 10^7$ years, and become $1\mathcal{M}_\odot$ in $\sim 3 \times 10^9$ years.

• *Postulating a Hydrodynamic Sun.* If the Sun is not in hydrostatic equilibrium, then the neutrino flux we observe today may not be linked to the current solar luminosity. (In other words, the

Sun must currently be undergoing changes on a Kelvin-Helmholtz timescale.) Two types of instabilities that could be invoked are

- Thermal Instabilities
- Hydrodynamic Phenomena

The former deals with thermal runaways (such as may occur if fusion goes as extremely high power of temperature); in the latter category are internal waves (such as g-mode oscillations) and turbulent motions.

• *Postulating Non-Standard Physics* In this category are speculations that are in conflict with laboratory measurements. Some possible physics includes

- Non-Maxwellian velocities
- Very different atomic cross-sections (*i.e.*, $S_{34} = 0$)

• *Neutrino Oscillations.* If neutrinos are not massless, then according to some Grand Unification Theories, electron neutrinos may change into another type of neutrino (muon or tau) on their way out of the Sun. In a vacuum, the probability of this happening to a neutrino is proportional to the "proper time" of its journey, *i.e.*,

$$\mathcal{P} \propto R = \frac{\text{path length}}{\text{Energy}}$$

Laboratory measurements of this proper time are sensitive to $R \sim 10^2$ km GeV^{-1}; the solar neutrinos have $R \sim 1.5 \times 10^8/10^{-3} \sim 10^{11}$ km GeV^{-1} to make their oscillations. Moreover, neutrino oscillations may be induced by interactions with electrons. [This is the Mikheyev-Smirnov-Wolfenstein (MSW) effect.] The column density of the Sun is $\sim 2 \times 10^{11}$ gm cm^{-2}; the largest laboratory column density is 2×10^8 gm cm^{-2}. Thus this hypothesis is difficult to test. (Note that the current limit on the electron neutrino mass, $m_\nu < 9$ eV, comes from the nuetrinos of SN 1987A.)