

Neutrinos from the Sun

Neutrino Astrophysics¹ in general is a controversial subject, but one branch of it should at least in principle be uncontroversial, namely the emission of neutrinos from the Sun. The only neutrinos involved are those emitted in ordinary nuclear beta decay, which is well understood. Furthermore, the total rate of emission of neutrinos by the Sun can be calculated quite accurately. No matter which specific links in the reaction chains dominate in the Sun, the overall effect is the conversion of hydrogen into helium,



The ratio between the number of neutrinos released and the energy produced is thus known accurately and we know the "solar constant", the flux at the Earth of electromagnetic radiation emitted by the Sun. The solar neutrinos reach us almost instantaneously, whereas the solar photons reaching us now came from nuclear reactions which occurred in the Sun's interior about 10^7 years ago. Nevertheless, this time delay of 10^7 years is very short compared with the age of the Sun (about 4.5×10^9 years) and it is generally assumed that the "solar constant" does not change in 10^7 years. The fraction of the energy release of Eq. (1) which goes into neutrinos depends on which of the individual reactions dominate, but this fraction is in any case rather small and close to 26 MeV of the energy release is converted into electromagnetic radiation. We then get for the total flux at the Earth of solar neutrinos

$$\phi_{\nu, \text{tot}} = 6.7 \times 10^{10} \nu/\text{cm}^2\text{-sec.} \quad (2)$$

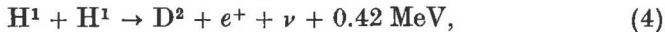
There are a number of possible ways of detecting solar neutrinos and Davis² some time ago picked as the most promising method the detection of radioactive argon made by the inverse beta decay of chlorine,



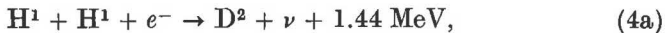
The cross section for this reaction, calculated by Bahcall,³ is a steeply increasing function of the kinetic energy E_ν of the neutrino. The cross

section is of course zero for E_ν below the threshold energy of 0.81 MeV and then rises fairly steeply because of the phase-space factors in the beta-decay formulae. Furthermore, the analogue state to the Cl^{37} ground state was predicted to lie at 5.1-MeV excitation energy in Ar^{37} , so that one has an additional superallowed channel contributing when E_ν exceeds 5.9 MeV. Although the total flux of solar neutrinos is given accurately by Eq. (2), the energy distribution of the neutrinos depends strongly on which individual reactions dominate in the Sun. The total production rate of Ar^{37} at the Earth then also depends strongly on the competition between the different reactions and this in turn depends strongly on the central temperature T_c of the Sun. This strong temperature sensitivity of the predicted rate makes the neutrino experiment more exciting and the work of the theorist more difficult.

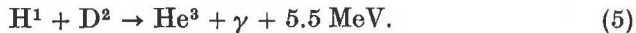
The possible links in the proton-proton reaction chain are as follows. The initiating reaction is overwhelmingly



with only a small admixture of

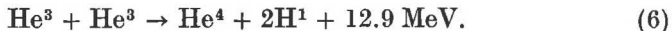


which has the same effect (the positron annihilates against an electron anyway) except for the increased neutrino energy. The second step is simply



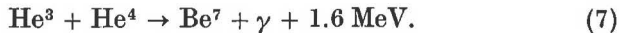
For the next step there are two possibilities.

(i) The dominant channel for the Sun is



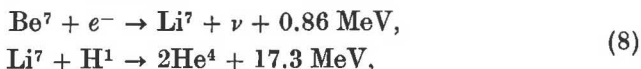
This reaction does not produce any neutrinos itself but, since it uses up two He^3 nuclei, two neutrinos from reaction (4) [or, occasionally, from (4a)] are produced per He^4 nucleus.

(ii) The alternative reaction to Eq. (6) is a two-step process of which the first is

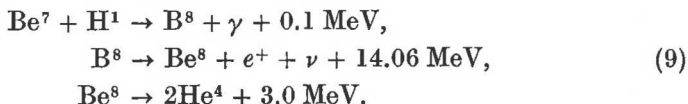


For the second step in this process there are again two alternatives:

(iii) the dominant step in the Sun is



and the rival reaction is (iv)



As mentioned above, by far the dominant neutrino flux in the Sun comes from Eq. (4) and these neutrinos are below the energy threshold for absorption on Cl^{37} , and the second most abundant neutrinos from Eq. (8) are only a little above threshold. The B^8 neutrinos from Eq. (9) have the highest energy and by far the greatest cross section σ for $\text{Cl}^{37} \rightarrow \text{Ar}^{37}$ absorption and by far the smallest flux ϕ_ν since the less probable branch is required both in the first and in the second step of the proton-proton chain. The present best theoretical estimates^{4,5} for the various neutrino fluxes ϕ_ν and cross sections σ for Cl^{37} absorption are given in Table I (including neutrinos from the beta decay of N^{13} from the carbon-nitrogen cycle which accounts for a few percent of the energy production in the Sun).

TABLE I

	$\text{H}^1 + \text{H}^1$ $\rightarrow e^+$	$\text{H}^1 + \text{H}^1$ $+ e^-$	Be^7	B^8	N^{13}	O^{15}	Total
ϕ_ν ($10^{10}/\text{cm}^2\text{-sec}$)	6.4	0.02	0.3	5×10^{-4}	0.02	0.02	6.7
σ (10^{-46} cm^2)	0	17.0	3.0	1.35×10^4	2.0	8.0	
$\phi_\nu \sigma$ ($10^{-36}/\text{sec}$)	0	0.3	0.9	6.2	0.2		7.5

As Table I shows, the total rate of Ar^{37} from terrestrial Cl^{37} is dominated by the B^8 neutrinos, in spite of their small flux. This flux is not only small but also highly uncertain: (a) In part because the flux is proportional to the cross-section factor S_{17} for the $\text{Be}^7(p, \gamma)\text{B}^8$ reaction in Eq. (9) and the assumed value of $S_{17} = 43 \text{ eV-barns}$ is not very accurately known, (b) The flux is a very steeply increasing function of the central temperature T_c of the Sun because the thermonuclear rate of the required $\text{Be}^7(p, \gamma)$ reaction depends strongly on temperature, whereas the successful rival reaction $\text{Be}^7(e^-, \nu)$ of course does not depend on temperature appreciably. To illustrate the great extent of the sensitivity: When the chlorine experiment^{2,3} was first planned a few years ago the theoretical estimate for $\sum \phi_\nu \sigma$ was about five times larger than at present. This change was brought about not by any radical change in the theory but merely by the refinement of the numerical values of a number of the input data used.

To make a precision calculation of the interior conditions in the Sun at present, especially of the central temperature T_c , one uses the accurately known values of the solar mass and present luminosity (the radius is also known accurately, but because of our poor understanding of the superadiabatic gradients in the Sun's outer layers we are unable to make use of the precision value of the radius). In the calculation one needs to know Z , the abundance (by mass) of all elements other than hydrogen and helium, which affects the opacity and hence the heat-flow equation and the cross-section factor S_{11} for the proton-proton reaction which affects the energy-production equation. If Z and S_{11} were known exactly and *if* the chemical composition were uniform throughout the Sun, one could calculate T_c (and also the uniform H/He abundance ratio) uniquely. In reality the Sun has converted some H into He, but only in its deep interior, and thus has a varying H/He ratio. One therefore has to do a full stellar evolution calculation, making sure one arrives at the correct luminosity L for the present time, and one usually assumes that the Sun started with a uniform composition 4.7×10^9 years ago and that the He produced since then has not been mixed with the outer layers.

The p - p reaction rate is proportional to the square of the hydrogen abundance X_c at the Sun's center, to the cross-section factor S_{11} , and to a positive power of temperature T_c . Since the total present energy-production rate must equal the known luminosity L , an increase in X_c or in S_{11} will decrease T_c . A few years ago the best value for S_{11} was 3.36×10^{-25} MeV-barns and for Z (obtained from solar spectroscopy) was about 0.03, which gave for the present Sun $T_c = 1.57 \times 10^7$ °K and $\sum \phi_\nu \sigma = 40 \times 10^{-36}$ sec $^{-1}$. The most recent estimates have raised S_{11} about 12% (largely due to a change in the measured neutron lifetime, used in calculating beta-decay coupling constants) and newer spectroscopic determinations suggest Z about 0.015 which lowers the helium abundance and hence raises X_c . Both changes tend to lower T_c which is now⁵ calculated as 1.49×10^7 °K, which leads to the value of $\sum \phi_\nu \sigma = 7.5 \times 10^{-36}$ sec $^{-1}$ in Table I. It is not clear how much smaller the remaining errors in Z and S_{11} (and in S_{17} , which also enters the calculations) now are. A factor of 2 (or even 4) up or down in $\sum \phi_\nu \sigma$ is quite possible even without any drastic change in the theory or any serious blunder in an experiment; a factor of more than 20 downward, however, would be most embarrassing since the value in the second column of Table I should be almost completely insensitive to temperature (the Be⁷ neutrinos lie in between in temperature sensitivity).

Now to the experiment itself^{2,6}: Davis put about 600 tons of C₂Cl₄ (a

dry-cleaning fluid) in a tank about 5000 feet underground (in a South Dakota gold mine) to reduce cosmic-ray background. After waiting about 40 or 50 days (the Ar^{37} half-life is 35 days) any argon in the liquid was purged with helium gas, then separated from the helium and the radioactive decay of any Ar^{37} in the remaining argon was counted. In this experiment a count of one decay per day would correspond to $\sum \phi_\nu \sigma = 6 \times 10^{-36} \text{ sec}^{-1}$. The sensitivity of the experiment is about one half of that, the counts to date have not significantly exceeded the expected background and thus we only have an upper limit to the experimental flux-cross-section product,

$$\sum (\phi_\nu \sigma)_{\text{exp}} < 3 \times 10^{-36} \text{ sec}^{-1}, \quad (10)$$

about one half of the present theoretical estimate.

The present state of affairs is most frustrating for all concerned. The original theoretical estimate of about 12 counts per day would have been easily and accurately measurable and the theoretical revisions could as easily have been up as down. They were down, however, and we have seen that a further factor of two down in the theoretical estimate is quite possible. Thus, at the present time we neither have a positive identification of solar neutrinos nor the morbid satisfaction of predicting a scandal in stellar evolution theory! One possible modification in the theory has already been suggested⁷: If the solar core is "spinning down", meridional circulation might mix the helium produced in the Sun's deep interior with the rest of the Sun. This would raise the present X_\odot and thus lower T_\odot slightly and the B^8 -neutrino flux would be lowered by a factor⁸ of about three (the Brans-Dicke theory of the variation of gravity *without* mixing, on the other hand, would increase the chemical inhomogeneity and raise the flux by about a factor of three). The sensitivity of the Davis experiment can be improved with time and, hopefully, will lead to positive detection of neutrinos (and not to the destruction of the theorists by increasing the discrepancy).

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