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Abstract

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THE PROTON-PROTON CYCLE AND SOLAR NEUTRINOS

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The primary task of the new field of science—neutrino astrophysics—is the detection of solar neutrinos. The energy spectrum and intensity of solar neutrinos depend on the type of processes occurring in the central region of the Sun. According to Bethe's estimate (^{1}), in main-sequence stars energy release is provided by the p—p- and C—N-cycles. In the C—N-cycle, two groups of neutrinos are emitted with energies $E_{\text{max}} = 1.18$ MeV and $E_{\text{max}} = 1.7$ MeV.

In the first reaction of the p—p-cycle,

$$\mathrm{H}^1(\mathrm{H}^1, e^+\nu)\mathrm{D}^2. \tag{1}$$

neutrinos are formed with $E_{\text{max}} = 0.42$ MeV. The next link of the cycle is the formation of He^3 by the reaction

$$\mathrm{D}^2(\mathrm{H}^1, \gamma)\mathrm{He}^3. \tag{2}$$

Further development of the cycle may proceed through different channels:

$$\mathrm{He}^3 + \mathrm{He}^3 \rightarrow \mathrm{He}^4 + 2\mathrm{H}^1; \tag{3a}$$

$$\begin{gathered} \mathrm{B}^7 + e^- \rightarrow \mathrm{Li}^7 + \nu, \quad \mathrm{Li}^7 + \mathrm{H}^1 \rightarrow 2\mathrm{He}^4, \\ \mathrm{He}^3 + \mathrm{He}^4 \rightarrow \mathrm{Be}^7 + \gamma, \\ \mathrm{Be}^7 + \mathrm{H}^1 \rightarrow \mathrm{B}^8 + \gamma, \quad \mathrm{B}^8 \rightarrow \mathrm{Be}^8 + e^+ + \nu, \quad \mathrm{Be}^8 \rightarrow 2\mathrm{He}^4. \end{gathered} \tag{3b}$$

When an electron is captured by a Be^7 nucleus, neutrinos with an energy of 0.86 MeV are formed, and in the decay of B^8—neutrinos with a maximum energy of 13.6 MeV.

To determine the probability of the various reactions of the p—p-cycle, besides the reaction cross sections, it is necessary to know the concentrations of the particles. The existing spectroscopic data give only the concentration values of hydrogen and He^4 in the outer atmosphere of the Sun. According to recent data, at the surface of the Sun the mass concentration of hydrogen is $X_{\mathrm{H}} = 0.630$, and that of helium is $X_{\mathrm{He}} = 0.336$ (^{2}). Taking into account that in the center of the Sun hydrogen is burned out by thermonuclear reactions and helium accumulates, in the present work it is assumed that $X_{\mathrm{H}} = X_{\mathrm{He}} = 0.47$.

Assuming that a dynamic equilibrium exists between the various successive reactions of the p–p-cycle, one can determine the concentrations of the particles participating in the reactions of the p–p-cycle. Table 1 gives the mass concentrations of particles relative to hydrogen. From the data of the table the durations of the reactions were calculated (Table 2). In doing so the density was assumed equal to $\rho = 145$ g/cm^3.

Table 1

Mass concentrations relative to hydrogen

	$5 \cdot 10^6$ °K	$10{\cdot}10^6$ °K	$15{\cdot}10^6$ °K	$20{\cdot}10^6$ °K	$25{\cdot}10^6$ °K	$20{\cdot}10^6$ °K
$X(\mathrm{D}^2)$	$0.96 \cdot 10^{-17}$	$0.64 \cdot 10^{-17}$	$0.52 \cdot 10^{-17}$	$0.46 \cdot 10^{-17}$	$0.42 \cdot 10^{-17}$	$0.40 \cdot 10^{-17}$
$X(\mathrm{He}^3)$	0.21	$9.68 \cdot 10^{-4}$	$5.91 \cdot 10^{-5}$	$5.03 \cdot 10^{-5}$	$4.41 \cdot 10^{-7}$	$6.60 \cdot 10^{-8}$
$X(\mathrm{Be}^7)$	$2.01 \cdot 10^{-17}$	$4.32 \cdot 10^{-13}$	$4.49 \cdot 10^{-11}$	$3.69 \cdot 10^{-10}$	$3.33 \cdot 10^{-10}$	$1.15 \cdot 10^{-10}$
$X(\mathrm{Li}^7)$	$7.23 \cdot 10^{-15}$	$6.35 \cdot 10^{-15}$	$4.96 \cdot 10^{-15}$	$4.35 \cdot 10^{-15}$	$1.87 \cdot 10^{-16}$	$1.20 \cdot 10^{-17}$
$X(\mathrm{B}^8)$	$2.41 \cdot 10^{-34}$	$7.51 \cdot 10^{-25}$	$2.27 \cdot 10^{-20}$	$6.14 \cdot 10^{-18}$	$8.48 \cdot 10^{-17}$	$1.55 \cdot 10^{-16}$

Table 2

Reaction durations

Reaction	$5 \cdot 10^6$ °K	$10{\cdot}10^6$ °K	$15{\cdot}10^6$ °K	$20{\cdot}10^6$ °K	$25{\cdot}10^6$ °K	$30{\cdot}10^6$ °K
$\mathrm{H}^1 + \mathrm{H}^1 \to \mathrm{D}^2 + e^+ + \nu$	$2.84{\cdot}10^{12}$ years	$7.72{\cdot}10^{10}$ years	$1.40{\cdot}10^{10}$ years	$4.86 \cdot 10^9$ years	$2.31 \cdot 10^9$ years	$1.32 \cdot 10^9$
$\mathrm{D}^2 + \mathrm{H}^1 \to \mathrm{He}^3 + \gamma$	430.00 sec	7.75 sec	1.15 sec	0.35 sec	0.15 sec	0.08 sec
$\mathrm{He}^3 + \mathrm{He}^3 \to \mathrm{He}^4 + 2\mathrm{H}^1$	$3.94{\cdot}10^{11}$ years	$5.08 \cdot 10^7$ years	$8.22 \cdot 10^5$ years	$2.48 \cdot 10^5$ years	$6.48 \cdot 10^4$ years	$5.70 \cdot 10^4$ years

Reaction	$5 \cdot 10^6$ °K	$10 \cdot 10^6$ °K	$15 \cdot 10^6$ °K	$20 \cdot 10^6$ °K	$25 \cdot 10^6$ °K	$30 \cdot 10^6$ °K
$He^3 + He^4 \to Be^7 + \gamma$	$3.78 \cdot 10^{15}$ years	$1.16 \cdot 10^9$ years	$8.29 \cdot 10^5$ years	$8.69 \cdot 10^3$ years	$3.42 \cdot 10^2$ years	29.19 years
$Be^7 + e^- \to Li^7 + \nu$	56.89 days	80.43 days	98.53 days	113.80 days	127.20 days	139.40 days
$Li^7 + H^1 \to B^8 + \gamma$	$3.45 \cdot 10^9$ years	$2.37 \cdot 10^4$ years	76.43 years	2.08 years	59.02 days	8.42 days
$Li^7 + H^1 \to 2He^4$	56.59 years	1.19 days	15.74 min	35.95 sec	6.21 sec	1.28 sec

Consideration of the data obtained shows that at a temperature $T \leq 5 \cdot 10^6$ °K, reactions (3a)—(3b) are not in dynamic equilibrium with reactions (1) and (2), since the duration of reaction (3a), $3.94 \cdot 10^{11}$ years, exceeds the age of stars accepted at the present time. This means that at $T = 5 \cdot 10^6$ °K the concentration of He^3 is smaller than the value given in Table 1.

Fig. 1. Dependence of the reaction probability on temperature. 1—the reaction $He^3(He^4, \gamma)Be^7$; along the ordinate is plotted the number of Be^7 atoms formed in one cycle; 2—the reaction $Be^7(H^1, \gamma)B^8$; along the ordinate is plotted the quantity $N(B^8)/N(Be^7)$, where $N(B^8)$ and $N(Be^7)$ are the numbers of B^8 and Be^7 atoms formed in one cycle.

Fig. 2. Rate of the $Cl^{37}(\nu, e^-)Ar^{37}$ reaction. 1—$X_{CN} = 0$, "normal" p—p cycle; 1′—$X_{CN} = 0$, "anomalous" p—p cycle; 2—$X_{CN} = 0.5\% \, X_H$, "normal" p—p cycle; 2′—$X_{CN} = 0.5\% \, X_H$, "anomalous" p—p cycle.

The reaction $Be^7(H^1, \gamma)B^8$ is of considerable interest, since the B^8 nucleus is a source of neutrinos of relatively high energy, $E_{\max} = 13.6$ MeV. As is evident from Fig. 1 and Table 2, with increasing temperature the contribution of this reaction grows strongly.

In addition to the reactions considered above, He^3 can absorb a proton with the formation of Li^4 (1), if such a nucleus exists at all:

$$He^3 + H^1 \to Li^4 + \gamma, \qquad Li^4 \to He^4 + e^+ + \nu. \tag{4}$$

Estimates show that the rate of reaction (4) greatly exceeds the rates of reactions (3a) and (3b). Therefore, if the Li^4 nucleus exists, the p—p cycle should end mainly with reaction (4). Interest in this reaction is not accidental. The point is that in this reaction high-energy neutrinos are formed, $E_{\max} \approx 18.9$ MeV, and it appears possible to register solar neutrinos already at the sensitivity of detection now achieved. In favor of the existence of Li^4, Tairen···

and Tyuv (³), who studied short-lived nuclei formed under the action of protons in lithium. The radioactive isotope with a period of 0.4 sec was interpreted by the authors as either Li^4 or Be^6. Since there are at present no other data, reaction (4) should be regarded as hypothetical.

The data obtained make it possible to determine the neutrino luminosity of stars with different central temperatures. To do this, using the dependence of energy release on temperature and taking into account the change in temperature and density along the radius of the star, the number of p—p and C—N cycles per second is determined. Then, having determined from the data of Table 2 and Fig. 1 the probabilities of the various branches of the cycle, we obtain the intensity of neutrinos of different energies at a given value of the temperature at the center of the star.

For experiment, an important quantity is the reaction rate, i.e., the product of the neutrino flux by the reaction cross section $\xi = I_\nu \sigma$ sec^{-1}. Figure 2 presents the dependence of the rate of the reaction $Cl^{37}(\nu, e^-)Ar^{37}$ on the temperature at the center of the Sun. Data are given for two cases: $X_{CN} = 0$ and $X_{CN} = 0.5\% \, X_H$. The "anomalous" p—p cycle, whose completion occurs by reaction (4), is also considered. The reaction cross section was determined from the formula given in work (⁴). The following values were obtained: $E = 0.86$ MeV, $\sigma \simeq 2.9 \cdot 10^{-46}$ cm^2; $E_{\max} = 13.6$ MeV, $\sigma_{av} \simeq 9 \cdot 10^{-44}$ cm^{-2}; $E_{\max} = 18.9$ MeV, $\sigma_{av} \simeq 1.8 \cdot 10^{-43}$ cm^2. For neutrinos emitted in the C—N cycle, $\sigma_{av} \simeq 10^{-45}$ cm^2. It is interesting to compare the obtained values of the neutrino flux with the data of work (²). In that work, values of the neutrino fluxes are given only at a temperature of $16.2 \cdot 10^6$ °K. For neutrinos with maximum energy 13.6 MeV the flux is $I_\nu(13.6) = 3.6 \cdot 10^7$ $\text{cm}^{-2} \cdot \text{sec}^{-1}$, and for monoenergetic neutrinos with $E = 0.861$ MeV, $I_\nu(0.861) = 1.0 \cdot 10^{10}$ $\text{cm}^{-2} \cdot \text{sec}^{-1}$. According to our data, at the same temperature $I_\nu(13.6) = 5.5 \cdot 10^7$ $\text{cm}^{-2} \cdot \text{sec}^{-1}$ and $I_\nu(0.861) = 1.4 \cdot 10^{10}$ $\text{cm}^{-2} \cdot \text{sec}^{-1}$. The agreement is satisfactory.

Let us consider the experimental possibility of detecting solar neutrinos. For detecting neutrinos from the Sun the most convenient reaction is the formation of Ar^{37} from Cl^{37}. This reaction was proposed by B. Pontecorvo as early as 1946 (⁵).

As a target one can use an inexpensive material—carbon tetrachloride. Consideration shows that the most dangerous background reaction is the formation of Ar^{37} under the action of protons: $Cl^{37}(p, n)Ar^{37}$. In order for the ratio of effect to background to be greater than 1, a shield of thickness not less than 4000 g/cm^2 is necessary. The exposure time of carbon tetrachloride is determined by the half-life of Ar^{37} and is 2-3 months. After exposure it is necessary to extract Ar^{37} and determine the number of atoms. To register small amounts of Ar^{37} it is convenient to use a proportional counter or a Geiger counter. With a counting-installation background of $5 \cdot 10^{-4}$ counts/sec, the required amount of carbon tetrachloride is 700 tons.

In conclusion let us consider the results of Davis' s experiments on the detection of solar neutrinos. As a target Davis used carbon tetrachloride, and as the Ar^{37} detector—a Geiger-Müller counter with a background of $5 \cdot 10^{-3}$ counts/sec. Beginning in 1954, Davis gradually increased the amount of carbon tetrachloride, bringing it in 1962 to 600 tons ([6,8,2]).* The negative result obtained by Davis in 1959 ([8]) makes it possible to estimate an upper limit for the rate of the reaction $Cl^{37}(\nu, e^-)Ar^{37}$: $\xi \leq 1.1 \cdot 10^{-33}$ sec^{-1}. Comparison of this value with the data obtained by us (Fig. 2) shows that in the Sun either the "anomalous" p—p cycle is absent, or the temperature at the center of the Sun is more than $25 \cdot 10^6$ °K and, along with the p—p cycle, the C—N cycle takes place. In this connection it would be very interesting to verify under laboratory conditions the existence of the nucleus Li^4.

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* The results of the latest experiments with 600 tons of CCl^4 are not known.

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