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Abstract

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PHYSICS

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ON THE QUESTION OF THERMOMETRY OF THE SOLAR INTERIOR IN NEUTRINO EXPERIMENTS

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1. The distribution of temperature over the mass (radius) of the Sun and the temperature at its center, obtained in calculating evolutionary sequences of stellar models, are determined by specifying an initial set of parameters, such as the original chemical composition of the matter, the time of evolution, etc. ⁽¹⁻⁵⁾. A number of the assumptions used in this procedure in principle cannot be checked ⁽³⁾. Registration of the neutrino flux from the Sun makes it possible to approach more directly the determination of certain structural parameters, in particular the temperature of the solar interior ^(6,7).
2. The magnitude of the effects produced by solar neutrinos in detectors with a high energy threshold is determined ^(8,13) by neutrinos from the decay $B^8(e^+\nu)Be^{8*}$ and, to a lesser extent, by neutrinos from $N^{13}(e^+\nu)C^{13}$, $O^{15}(e^+\nu)N^{15}$, and $Be^7(e^-\nu)Li^7$. The contribution of neutrinos from other reactions does not exceed a few percent in the most widely discussed models of the Sun ⁽⁴⁾. Detectors for high-threshold neutrinos are Cl^{37} ($E_\nu^{thr} = 0.816$ MeV) in the Pontecorvo-Davis method ⁽⁹⁾, detectors of electrons from β -processes on the nuclei H^2 , Li^7 , etc., and of recoil electrons in the process of neutrino scattering on electrons $\nu + e^- \rightarrow \nu + e^-$ ⁽¹⁰⁾. In low-threshold detectors, such as Ga^{71} ($E_\nu^{thr} = 0.237$ MeV), the magnitude of the effect is determined by neutrinos from the reactions $Be^7(e^-\nu)Li^7$, $H^1(p, e^+\nu)H^2$, and in hot models also by $N^{13}(e^+\nu)C^{13}$, $O^{15}(e^+\nu)N^{15}$. As will be seen below, the possibilities of thermometry are associated in the first case with B^8 -neutrinos, and in the second with Be^7 -neutrinos.
3. Thermometry of the solar interior with the aid of neutrinos proves possible because the intensity of the principal neutrino fluxes (B^8 -neutrinos when working with high-threshold detectors and Be^7 -neutrinos when working with Ga^{71}) is determined mainly by the temperature of the central regions of the star. This is connected, in turn, with the following circumstances:

Fig. 1

Figure 1: Fig. 1

I. The contribution of the $Be^7(p, \gamma)B^8(e^+\nu)Be^{8*}(\alpha)He^4$ termination of the pp-cycle to the total energy release of the Sun is small at $T_c < 18 \cdot 10^6$ °K and does not determine its structure ⁽⁴⁾; similarly, for thermometry of the Sun in the region $T_c < 17 \cdot 10^6$ °K with the aid of low-threshold detectors (Ga^{71}), it is essential that the contribution to the energy release of the $He^3(\alpha, \gamma)Be^7$ termination of the pp-cycle should not be dominant, which apparently is the case in this temperature region.

II. The intensity of the generation of B^8 -neutrinos and Be^7 -neutrinos under this condition is determined to a significantly greater extent by the temperature of the matter in which the thermonuclear reactions proceed than by other factors.

III. The size of the regions in which effective generation of B^8 -neutrinos and Be^7 -neutrinos occurs is relatively small, amounting in Sears' model ⁽⁴⁾ to $M_{\text{eff}}(B^8) \approx 0.03M_\odot$ ($0 \leq r \leq 0.08R_\odot$) and $M_{\text{eff}}(Be^7) \approx 0.06M_\odot$ ($0 \leq r \leq 0.12R_\odot$) for B^8 - and Be^7 -neutrinos, respectively, where M_{eff} is the effective mass of the Sun in which neutrinos of the given kind are generated ⁽¹¹⁾.

4. The magnitude of the effect $Cl^{37}(\nu, e^-)Ar^{37}$ under the action of solar neutrinos for different models of the Sun ⁽⁴⁾ is shown in Fig. 1. The points show the results of calculations for detailed models of the Sun ^(4,2,14,18). The curves are constructed from extrapolation formulas of the form ⁽⁶⁾

$$\Phi_2(i) \cong \Phi_1(i) \frac{[n_{\nu \max}^i]_2 [\varepsilon_c]_1}{[n_{\nu \max}^i]_1 [\varepsilon_c]_2}, \quad (1)$$

where Φ_1 and Φ_2 are the neutrino fluxes of the i -th type in two models of the Sun; $n_{\nu \max}^i$ is the intensity of the neutrino flux of the i -th type emitted by 1 g of matter in 1 sec in the region of maximum generation; ε_c is the energy release per unit mass of matter at the center of the Sun. The quantities entering into (1) are determined by the corresponding values of the temperature and element concentrations. The degree of freedom needed by us for constructing a set of solar models is associated in particular with the variation of the content of heavy elements Z . Extrapolation of the calculations of neutrino fluxes ⁽⁴⁾ to the region $T_c \sim 14 \cdot 10^6$ °K is justified by the uncertainty of Z and by the lack of clarity in the question of mixing of matter in the region of the solar core.

Fig. 1. Dependence of the magnitudes of the effects $Cl^{37}(\nu, e^-)Ar^{37}$ and $Li^7(\nu, e^-)Be^7$, $Ga^{71}(\nu, e^-)Ge^{71}$ on the structure of the model of the Sun, characterized by the value of the central temperature T_c . The points show the results of calculations of the intensities of the fluxes of B^8 - and Be^7 -neutrinos in detailed models of the Sun; the curves are constructed from extrapolation formulas (1).

Dashed curves show the effects on Cl^{37} , dotted curves—on Ga^{71} . a — ∂ —models of Sears ⁽⁴⁾, obtained by variation of Z (a), age (σ) $5.5 \cdot 10^9$ years (b), luminosity $L = 0.97 L_{\odot}$ (v), parameter S (3.3) (g), and opacity (∂); e — z —models ⁽¹⁸⁾ (e), ⁽¹⁴⁾ (zh), and ⁽²⁾ (z); i —Davis experiment ⁽⁹⁾.

Extrapolation to the region $T_c \sim 18 \cdot 10^6$ °K is justified by a possible high content of heavy elements at the center of the Sun, $Z > 0.04$, by the uncertainty in the age of the Sun ^(4,5) and by variation of the gravitational constant ⁽¹²⁾, as well as by a number of other uncertainties ^(3,4). From Fig. 1 it is seen that the intensity of the flux of B^8 -, Be^7 - and N^{13} -, O^{15} -neutrinos in models with a high central temperature is significantly higher than in “cold” models; for the fluxes of $\text{He}^3 p$ - and pp -neutrinos the situation is the opposite. At $T_c = 15.7 \cdot 10^6$ °K the contributions of B^8 - and Be^7 -neutrinos to the magnitude of the effect $\text{Cl}^{37}(\nu, e^-)\text{Ar}^{37}$ are about 90 and 7%, respectively ⁽⁸⁾. At higher temperatures the ratio of the contributions changes still further toward predominance of B^8 -neutrinos. Fig. 1 also presents the values of $\Phi\sigma$ for the evolutionary sequence of solar models ⁽¹⁴⁾. Of course, for

In this case the luminosity of the star during its evolution does not remain constant, increasing by approximately a factor of 1.4.

5. The results concerning B^8 -neutrinos are affected most strongly, as is seen from Fig. 1, by the uncertainty in the value of the parameter $S(3,3)$, connected ⁽¹⁵⁾ with the cross section of the reaction $\text{He}^3(\text{He}^3, 2p)\text{He}^4$, which, according to ⁽¹⁵⁾, amounts to a factor of $5 \div 10$, and by the uncertainty in the value of the parameter $S(7,1)$ of the reaction $\text{Be}^7(p, \gamma)\text{B}^8$, which amounts ⁽¹⁶⁾ to $\pm 30\%$. When $S(3,3)$ is decreased by a factor of 5, the intensity of the B^8 -neutrino flux increases by $\simeq 40\%$ in comparison with another model with the same central temperature. Variations of age have a smaller effect, i.e., of the distribution of the concentrations of hydrogen and helium over the mass of the Sun, and variations of opacity and luminosity change the magnitude of the effect by $\pm 10\%$. The uncertainty in the value of the parameter $S(3,4)$ of the reaction $\text{He}^3(\alpha, \gamma)\text{Be}^7$ is small and, according to ⁽¹⁷⁾, is about $\pm 10\%$. Therefore the uncertainty in the Be^7 -neutrino flux is connected mainly with the uncertainty of $S(3,3)$, owing to the change in the concentration of He^3 and in the structure of the star, amounting to approximately 60% at $T_c \approx 16.3 \cdot 10^6$ °K; the remaining uncertainties are less significant, $\lesssim 5\%$. For the $\text{He}^3 p$ -neutrino flux ^{(20)*} the principal uncertainties are those in the values of the nuclear parameters $S(3,3)$ and $S(3,1)$. For the purposes of thermometry with the aid of high-threshold detectors it is, above all, urgently necessary to reduce the uncertainties in the values of $S(3,3)$ and $S(7,1)$.

6. Having measured experimentally the magnitude of the effect $\text{Cl}^{37}(\nu, e^-)\text{Ar}^{37}$ with an accuracy of $\pm 25\%$ (the limit is imposed not by the insufficiency of statistics, but by the uncertainty** of the neutrino absorption cross section by the Cl^{37} nucleus), one can fix the central temperature of the

Sun with an accuracy of $\pm 2\%$. Using as detecting reactions $H^2(\nu, pe^-)H^1$, $Li^7(\nu, e^-)Be^7$, etc., the neutrino absorption cross sections in which can be calculated with greater accuracy ($\pm 10\%$), one could increase the accuracy of determining the central temperature. However, the uncertainties in the values of the parameters of nuclear reactions in the solar interior, discussed in the preceding point, do not allow this to be done more accurately than $\pm 5\%$ in the vicinity of $T_c \sim 16 \cdot 10^6$ °K. For $T_c < 15 \cdot 10^6$ °K, thermometry by the Pontecorvo-Davis method is made difficult because of the falling statistics of events caused by B^8 -neutrinos. The constancy of the temperature during a cycle of measurements can be confirmed with an accuracy determined by the statistical reliability of the results, i.e., in the Pontecorvo-Davis method with 4000 tons of C_2Cl_4 , constancy over, say, a year can be recorded with an accuracy of $\pm 0.3\%$, or $\pm 5 \cdot 10^4$ °K. Thermometry by means of the method $Ga^{71}(\nu, e^-)Ge^{71}$ is possible in the temperature range $T_c \approx (14 \div 18) \cdot 10^6$ °K, although with lower accuracy than with detectors sensitive to B^8 -neutrinos ($\pm 4\%$ when the magnitude of the effect is fixed with an accuracy of $\pm 25\%$). Moreover, the cross sections of transitions to the excited states of Ge^{71} are known with less reliability than for the transitions $Cl^{37} \rightarrow Ar^{37*}$. The temperature dependence of the magnitudes of the effects $Cl^{37}(\nu, e^-)Ar^{37}$ and $Li^7(\nu, e^-)Be^{37}$ is determined approximately by T_c^{13} , and that of the effect $Ga^{71}(\nu, e^-)Ge^{71}$ by approximately T_c^7 in the vicinity of $T_c \approx 16 \cdot 10^6$ °K.

7. We can now interpret the results of Davis' s experiment ⁽⁹⁾ in terms of an upper limit for the central temperature of the Sun. The straight line *D* in Fig. 1 represents Davis' s results with the corresponding statistical uncertainty. It is also necessary to take into account the uncertainty in the absorption cross section of solar neutrinos by the Cl^{37} nucleus. As a result we find that, according to these measurements, the central temperature does not exceed $T_c \lesssim (18 \pm 2) \cdot 10^6$ °K. It should be noted that this limit is very

* C. W. Werntz, private communication.

** The cross sections for transitions to excited states of Ar^{37} were taken by us from work ⁽⁸⁾. In calculating the magnitude of the effect $Li^7(\nu, e^-)Be^7$, transitions to the ground and $1/2^+$, (0.431 MeV) excited states of Be^7 were included. Transitions to the excited level (0.175 MeV) of the Ge^{71} nucleus were included approximately.

closely adjoins the results obtained in calculations of solar models with a relatively high content of heavy elements, $Z \simeq 0.04$. It is probable that models with $Z > 0.04$ are already excluded, if only because there is no convective core in the center of the Sun ⁽¹⁹⁾. An improvement in the experimental possibilities by a factor of 3-10 will make it possible to proceed closely to an analysis of the assumptions presently used in calculating solar models.

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Note added in proof. In ⁽²¹⁾ it was found that the rate of the reaction $\text{Be}^7(p, \gamma)\text{B}^8$ had been overestimated ⁽¹⁶⁾ by approximately a factor of 2. Taking this circumstance into account leads to the fact that the magnitudes of the effects $\text{Cl}^{37}(\nu, e^-)\text{Ar}^{37}$ and $\text{Li}^7(\nu, e^-)\text{Be}^7$ decrease by a factor of 2; from Fig. 1 it is seen that interpretation of the available Davis data ⁽⁹⁾ in terms of a limit on T_c becomes difficult.

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