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COMPUTATION OF THE NUMBER OF NEUTRINO EVENTS WHICH CAN BE REGISTERED IN BOREXINO DETECTOR FROM THE SUN NEUTRINO FLUX WITH ENERGY $E_\nu = 0.862$ MeV

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Расчет числа нейтринных событий, которые будут регистрироваться
на детекторе «Борексино» от потока солнечных нейтрино
с энергией $E_\nu = 0{,}862$ МэВ

Проводится расчет числа нейтринных событий $N^{\rm theor}$, которые будут регистрироваться на детекторе «Борексино» от солнечных нейтрино с энергией $E_{\nu_e} = 0{,}862$ МэВ, генерированных в реакции $^7{\rm Be}+e^- \to {}^7{\rm Li}+\nu_e$ при отсутствии осцилляции нейтрино. Это число находится в пределах $N^{\rm theor} = 86{,}45 \div 96{,}52$ случаев/(сут $\cdot$ 100 т) в зависимости от потока солнечных нейтрино. Отношение между числом нейтрино $N^{\rm exper}$, зарегистрированных на детекторе «Борексино», и рассчитанным числом равно $N^{\rm exper}/N^{\rm theor} = 0{,}49 \div 0{,}54$. Эта величина достаточно близка к той же величине, полученной в эксперименте ^{71}Ga–^{71}Ge в близкой энергетической области. Величина $N^{\rm exper}/N^{\rm theor}$, полученная в предположении, что $\theta_{13} \approx 0$, и в отсутствие осцилляций нейтрино, равна $\simeq 0{,}67$ и заметно выше, чем приведенная величина. Это означает, что $\theta_{13} \neq 0$, и тогда должен присутствовать вклад от τ-нейтрино.

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Computation of the Number of Neutrino Events Which Can Be Registered
in Borexino Detector from the Sun Neutrino Flux with Energy $E_\nu = 0.862$ MeV

This paper gives an estimation of the number of neutrinos which can be registered in Borexino detector from the Sun neutrinos generated in reaction $^7{\rm Be}+e^- \to {}^7{\rm Li}+\nu_e$ with energy $E_{\nu_e} = 0.862$ MeV in the absence of neutrino oscillations. This number is supposed to be in the range $N^{\rm theor} = 86.45 \div 96.52$ counts/(day $\cdot$ 100 t) in dependence on primary neutrino fluxes. Then ratios between the number of neutrinos $N^{\rm exper}$ registered in Borexino detector and counted numbers $N^{\rm theor}$ are $N^{\rm exper}/N^{\rm theor} = 0.49 \div 0.54$. This value is close enough to the same value obtained in ^{71}Ga–^{71}Ge experiments in the close energy region. The value $N^{\rm exper}/N^{\rm theor}$ obtained at the supposition that $\theta_{13} \approx 0$ and in the absence of the resonance effect approximately equals $\simeq 0.67$ and it is noticeably greater than the above value. Probably it means that the supposition that $\theta_{13} \approx 0$ is not justified and there can be a definite deposit of τ neutrinos.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

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1. INTRODUCTION

In the present time the detector Borexino goes on operating [1, 2]. One of the major tasks of this detector is to measure a Sun neutrino flux with energy $E_\nu = 0.862$ MeV, appearing in the reaction $^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$. Measurements of the neutrino flux at this energy are very important since in this energy region the deposit of the resonance mechanism of neutrino oscillations is very small [3, 4]. Then if it is supposed that the mixing angle is $\theta_{13} \approx 0$, only electron neutrino vacuum oscillations can be observed in this case. Usually it is supposed that the deficit of high-energy Sun neutrinos is caused by the resonance mechanism of neutrino oscillations in the Sun matter.

The value of $\sin^2 2\theta_{12}$ obtained in work [5] from the reactor experiment (neutrino vacuum oscillations) is

$$\sin^2(2\theta_{12}) \simeq 0.83, \tag{1}$$

then the fraction (part) of electron neutrinos P_{ν_e} is

$$P_{\nu_e} = 1 - \frac{1}{2}\sin^2(2\theta_{12}) \simeq 0.615, \tag{2}$$

and the remaining neutrinos are muon ones and a relative portion P_{ν_μ} of these neutrinos is

$$P_{\nu_\mu} = \frac{1}{2}\sin^2(2\theta_{12}) \simeq 0.385. \tag{3}$$

If electron neutrinos are registered via the charged current, then $P_{\nu_e}(W)$ must be equal to 0.615. But if neutrinos are registered via the charged and neutral currents (as is the case in Borexino experiment), we must add the deposit of neutral current from the electron and muon neutrinos, then $P_{\nu_e}(Z^0) \simeq 0.155$ (see the value obtained in SNO [6]) and

$$P_{\nu_e}(W, Z^0) \simeq 0.615 + 0.155 = 0.770. \tag{4}$$

In Borexino detector, neutrinos are registered via the neutral and charged currents. If the primary neutrino flux is N_e^0 electron neutrinos, then with no neutrino oscillations this detector can register n neutrinos, which is a sum of events registered via neutral current n^0 and charged current $n^{\text{neutral}} = 0.155 \cdot n^0$ (value 0.155 is relative portion of neutrinos generated by neutral current), and then

$$n = n^0 + n^{\text{neutral}} = (1 + 0.155)n^0. \tag{5}$$

If $\theta_{13} \approx 0$ and there are electron neutrino oscillations, then via the charged current $n^{\text{charged}} = n^0 P_{\nu_e}$ neutrinos can be registered and via the neutral current $n^{\text{neutral}} = 0.155 \cdot n^0$ neutrinos (all electron and muon neutrinos interact via neutral current) can be registered and the sum of neutrinos which can be registered in Borexino detector is

$$n^{\text{osc}} = n^{\text{charged}} + n^{\text{neutral}} = (P_{\nu_e} + 0.155)n^0. \tag{6}$$

The ratio between n^{osc} and n is

$$\frac{n^{\text{osc}}}{n} = \frac{(P_{\nu_e} + 0.155)}{(1 + 0.155)} = 0.667. \tag{7}$$

This value is the value which can be obtained in Borexino detector if $\theta_{13} \approx 0$ and there are only oscillations of electron neutrinos.

In work [1] it was reported that Borexino detector must detect about 55 counts/(day$\cdot$100 t) of neutrino events in the absence of the resonance effect, then the following work [2] reported that this detector must detect (75 ± 4) counts/(day $\cdot$ 100 t) in the absence of neutrino oscillations.

The purpose of this work is an independent estimation of the number of neutrino events which can be registered in Borexino detector from the Sun neutrino flux with energy $E_\nu = 0.862$ MeV in the absence of neutrino oscillations.

From the experiments we know that the mixing angle of $\theta_{23} \simeq \pi/4$ (45°) [7, 8] and $\theta_{12} \simeq 32°$ [5]. The author holds the point of view that since the above (other) mixing angles are big, then there is no reason to suppose that the third angle of mixing θ_{13} can be very small (for analysis of situation with this supposition see in work [9]).

2. FLUX OF THE SUN NEUTRINOS FROM ^{7}Be + e^- → ^{7}Li + ν_e REACTION COMPUTED IN THE FRAMEWORK OF THE STANDARD SUN MODEL

The discussion of the Standard Sun Model (SSM) was given by J. Bahcall in [10]. The flux of the Sun neutrinos from the reaction $^7\text{Be} + e^- \to {}^7\text{Li} + \nu_e$ obtained in [10] is

$$N_{\nu_e}^{\text{theor}} = 0.47(1 \pm 0.15) \cdot 10^{10} \text{ cm}^{-2} \cdot \text{s}^{-1}. \tag{8}$$

Afterwards the neutrino flux from this reaction was recalculated [3, 11] and the resulting values of $N_{\nu_e}^{\text{theor}}$ were

$$N_{\nu_e}^{\text{theor}\,1} = 0.455 \cdot 10^{10} \text{ cm}^{-2} \cdot \text{s}^{-1}, \tag{9}$$

and

$$N_{\nu_e}^{\text{theor}\,2} = 0.508 \cdot 10^{10} \text{ cm}^{-2} \cdot \text{s}^{-1}. \tag{10}$$

In our computations (estimations) we will use the above values for $N_{\nu_e}^{\text{theor}}$.

3. $\nu_e + e^- \to \nu_e + e^-$ ELASTIC SCATTERING CROSS SECTION

The elastic scattering of electron neutrino on electron is realized via W (charge current) and Z (neutral current) boson exchanges. In literature they usually take differential cross section and elastic cross section obtained in [12] (see also Ref. [13]). Then the expression for differential cross section takes the following form:

$$\frac{d\sigma_{\nu_e e}(W,Z)}{dT} = \frac{2m_e G_F^2}{\pi}\left[\left(\frac{1}{2}+\xi\right)^2 + \xi^2\left(1-\frac{T}{E_{\nu_e}}\right)^2 - \right.$$
$$\left. - \left(\frac{1}{2}+\xi\right)\xi\frac{m_e T}{E_{\nu_e}^2}\right], \quad (11)$$

and the expression for the elastic cross section is

$$\sigma_{\nu_e e}(W,Z) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}+\xi\right)^2 + \frac{1}{3}\xi^2\right], \quad (12)$$

where G_F is Fermi constant, $\xi = \sin^2\theta_W$, $t = (k_1 - k_2)^2 = (p_2 - p_1)^2$ (if electron is at rest, then $t = 2m_e^2 + 2m_e E_{e2}$, $s = (k_1 + p_1)^2$ (if electron is at rest, then $s = m_e^2 + 2m_e E_{\nu_e}$), $T = (E_{2e} - m_e)$ is kinetic energy of the scattered electron.

The expression for cross sections taking into account radioactive corrections is given in [14]. We will not use these corrections since the uncertainty in the calculated flux of the Sun neutrinos considerably exceeds these corrections.

The expression for elastic cross section (12) after substitution of the value of s has the following form:

$$\sigma_{\nu_e e}(W,Z) = \frac{G_F^2 m_e^2}{\pi}\left(1 + 2\frac{E_{\nu_e}}{m_e}\right)\left[\left(\frac{1}{2}+\xi\right)^2 + \frac{1}{3}\xi^2\right] \simeq$$
$$\simeq \frac{G_F^2 m_e^2}{\pi} 2\left(\frac{E_{\nu_e}}{m_e}\right)\left[\left(\frac{1}{2}+\xi\right)^2 + \frac{1}{3}\xi^2\right] =$$
$$= 1.722\cdot 10^{-44} E_{\nu_e}(\mathrm{MeV})\left[\left(\frac{1}{2}+\xi\right)^2 + \frac{1}{3}\xi^2\right]\ \mathrm{cm}^2. \quad (13)$$

It is necessary to remark that this expression for the cross section is correct only at high energies when $E_{\nu_e} \gg m_e$. At low energies we must take the threshold effect into account, and then E_{ν_e} must be changed by

$$E_{\nu_e} \to \frac{E_{\nu_e}}{1 + \dfrac{m_e}{2E_{\nu_e}}}.$$

Then

$$\sigma_{\nu_e e}(W,Z) = 1.722 \cdot 10^{-44} \frac{E_{\nu_e}(\text{MeV})}{1+\dfrac{m_e}{2E_{\nu_e}}} \left[\left(\frac{1}{2}+\xi\right)^2 + \frac{1}{3}\xi^2 \right] \text{ cm}^2. \quad (14)$$

The average value for ξ [15] is $0.232 \div 0.234$. However, it is necessary to remark that for the best fitting expression (12) to the experimental data measured in [16, 17] for $\nu_e + e^- \to \nu_e + e^-$ elastic cross section, this value must be $\sin^2\theta_W = 0.248$. Therefore, in our computations (estimations) we will use this value for ξ. Then the value for expression $\left[\left(\frac{1}{2}+\xi\right)^2 + \frac{1}{3}\xi^2 \right]$ is 0.581. At $E_{\nu_e} = 0.862$ MeV, $\sigma_{\nu_e e}(W,Z) = 0.665 \cdot 10^{-44}$ cm^2 (now it is not necessary to use radioactive corrections since we have made normalization for the cross section measured in experiments [16, 17]).

In literature there is another expression for $\nu_e + e^- \to \nu_e + e^-$ elastic scattering [18]. These expressions coincide at high energies E_{ν_e}, but they differ at low energies E_{ν_e}. Probably, it is necessary to find out the reason of their discrepancies.

4. CHARACTERISTICS OF LIQUID SCINTILLATOR OF BOREXINO DETECTOR

Borexino detector uses trimethylbenzene $C_6H_3(CH_3)_3$ (or C_9H_{12}) and as scintillator $C_{15}H_{11}NO$ (1.5 g/l) [1, 2] is used. The density of trimethylbenzene is $\rho = 0.8761$ g $\cdot$ cm^{-3} (in our calculations we will not take into account this small addition related with the scintillator). The molecular weight of trimethylbenzene is $B = 120.19$ g $\cdot$ mol^{-1}. Then number of $C_6H_3(CH_3)_3$ molecules n_M in 1 cm^3 is

$$n_M = \frac{\rho}{B} N_A = 4.389 \cdot 10^{21}, \quad (15)$$

where N_A is the Avogadro number.

One molecule of $C_6H_3(CH_3)_3$ includes 66 electrons, then the number of electrons n_e in 1 cm^3 of trimethylbenzene (i. e., electron density) is

$$n_e = 2.897 \cdot 10^{23} \text{ cm}^{-3}, \quad (16)$$

then 100 t ($G = 10^5$ g) of trimethylbenzene contains

$$N_e = \frac{n_e G}{\rho} = 3.307 \cdot 10^{31} \text{ electrons}. \quad (17)$$

5. ESTIMATION OF THE NUMBER OF NEUTRINOS WHICH CAN BE REGISTERED IN BOREXINO DETECTOR FROM THE SUN NEUTRINOS WITH E_{ν_e} = 0.862 MeV

Using the previous computations, we estimate now the number of neutrinos N_B (event rates) which can be registered in the Borexino detector in 100 t of trimethylbenzene during one day ($t = 8.64 \cdot 10^4$ s).

$$N^{1\,\text{theor}} = N_e \cdot \sigma_{\nu_e e}(W, Z, 0.862\ \text{MeV}) \cdot t \cdot N_{\nu_e}^{\text{theor}\,1} = 86.45, \tag{18}$$

and

$$N^{2\,\text{theor}} = N_e \cdot \sigma_{\nu_e e}(W, Z, 0.862\ \text{MeV}) \cdot t \cdot N_{\nu_e}^{\text{theor}\,2} = 96.52. \tag{19}$$

So, the above estimations have shown that the event rates on 100 t/day in Borexino detector from the Sun neutrinos with $E_{\nu_e} = 0.862$ MeV can be as follows:

$$N^{\text{theor}} = 86.45 \div 96.52\ \text{counts}/(\text{day} \cdot 100\ \text{t}). \tag{20}$$

In [2] it was reported that the rate of events registered in this detector is

$$N^{\text{exper}} = 47 \pm 7(\text{stat.}) \pm 12(\text{syst.})\ \text{counts}/(\text{day} \cdot 100\ \text{t}). \tag{21}$$

Thus, the portion of neutrinos N^{exper} registered in this experiment relative to the computations in the framework of SSM are

$$\frac{N^{\text{exper}}}{N^{\text{theor}}} = 0.49 \div 0.54. \tag{22}$$

This value is close enough to the same value obtained in ^{71}Ga–^{71}Ge experiments [19, 20] in the energy regions near to the above one.

The value for $N^{\text{exper}}/N^{\text{theor}}$ in expression (22) is noticeably smaller than the value 0.67 obtained in expression (7) if it is supposed that $\theta_{13} \approx 0$. Probably it means that this supposition is not justified and there can be a definite deposit of τ neutrinos.

6. CONCLUSION

In this work the number of neutrinos which can be registered in Borexino detector from the Sun neutrinos generated in reaction $^7\text{Be} + e^- \to {}^7\text{Li} + \nu_e$ with energy $E_{\nu_e} = 0.862$ MeV has been calculated. This number is between

$$N^{\text{theor}} = 86.45 \div 96.52\ \text{counts}/(\text{day} \cdot 100\ \text{t}), \tag{23}$$

in dependence on the primary neutrino fluxes. Then the ratios between neutrinos N^{exper} registered in this experiment and the calculated numbers N^{theor} are as follows:

$$\frac{N^{\text{exper}}}{N^{\text{theor}}} = 0.49 \div 0.54 \tag{24}$$

This value is close enough to the same value obtained in ^{71}Ga–^{71}Ge experiments [19, 20] in the close energy regions. The value $N^{\text{exper}}/N^{\text{theor}} \simeq 0.67$ obtained in (7) at the supposition that $\theta_{13} \approx 0$ and the resonance effect is absent is noticeably larger than the value in (24). Probably, it means that the supposition that $\theta_{13} \approx 0$ is not justified and there can be a definite deposit of τ neutrinos.

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