Interaction of electron neutrino with LSD detector

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Abstract The interaction of electron neutrino flux, originating in the rotational collapse mechanism on the first stage of Supernova burst, with the LSD detector components, such as ^{56}Fe (a large amount of this metal is included in as shielding material) and liquid scintillator C_nH_{2n+2}, is being investigated. Both charged and neutral channels of neutrino reaction with ^{12}C and ^{56}Fe are considered. Experimental data, giving the possibility to extract information for nuclear matrix elements calculation are used. The number of signals, produced in LSD by the neutrino pulse of Supernova 1987A is determined. The obtained results are in good agreement with experimental data. .

Keywords: Supernova Burst, Neutrino Signal, Charged Current and Neutral Current Interaction

1. Introduction

SN1987A is the first and till now the only deep space object which have been observed both in electromagnetic and neutrino light. The possibility of SN neutrino observation was considered for the first time in [1]. The neutrino signals of SN1987A were registered on February, 23, 1987 by LSD [2], Baksan [3], KII [4] and IMB [5] detectors. The review and analysis of these experimental data is presented in [6]. LSD and BUST are liquid scintillator detectors, containing, correspondingly, in their work volumes 90 and 130 tons of liquid scintillator C_nH_{2n+2}, n=10, elaborated by A.V. Voevodskiy, V.L. Dadykin, O.G. Ryazhskaya [7]. KII and IMB are the water Cherenkov detectors with work volumes of 2140 and 5000 m^3.

On February, 23, 1987 LSD detected 5 neutrino events at 2.52 UT and 2 signals at 7.36 UT, BUST registered one signal at 2.52 UT and 6 signals at 7.36 UT , KII recorded 12 events at 7.35 UT and IMB – 8 signals at 7.35 UT. The two observed sets of neutrino signals with relatively large time separation of 4 h 44 min can be naturally explained on the base of the rotating mechanism of Supernova explosion [8]. In this mechanism the two-stage collapse occurs with time difference of ~ 5 h. The neutrino flux during the first burst consists of electron neutrinos with the total energy $W_{\nu_e} = 8.9 \times 10^{52}$ erg. The neutrino energy spectrum is hard with an average energy of ~ 30–40 MeV. The second neutrino burst corresponds to the standard collapse theory without rotation with formation of a neutrino sphere and with an equal energy distribution between all types of neutrinos [9]. Below a theoretical analysis of interaction of electron neutrino, originating from the first stage of gravitational collapse, with LSD detector is presented.

2. Neutrino Interaction

2.1. Interaction with ^{56}Fe

LSD detector contains 90 tons of scintillator for antineutrino observation by the reaction

$$\overline{\nu_e} + p \rightarrow n + e^+,$$
$$n + p \rightarrow d + \gamma, \quad E_\gamma = 2.2\,\text{MeV}, \quad \tau_C = 170\ \mu\text{s}.$$

LSD could measure both particles in this reaction. Also the detector contains about 200 t of ^{56}Fe as a shielding material. Under the impact of neutrino flux electrons and gamma quanta would be produced as a result of reaction with iron nuclei and they could be registered by the detector [10]. So, the following charge-exchange reaction takes place:

$$\nu_e + {}^{56}Fe \rightarrow {}^{56}Co^* + e^- \tag{1}$$

Due to neutrino interaction, excitation of analog 0^+ and Gamow–Teller 1^+ giant resonances in ^{56}Co results [11], that gives rise to gamma quanta production with energies of ~5 ÷10 MeV, together with electrons emission. The cross section of reaction (1) caused by charged current was calculated in [12]. In order to compare the produced estimations with experimental data, the theoretical cross section was averaged over the muon-decay-at-rest neutrino spectrum. The corresponding value is $2.62\cdot10^{-40}$ cm^2, which is in agreement with the KARMEN experiment result (2.56 ± 1.08(stat) ± 0.43(syst)) $\times\ 10^{-40}$ cm^2 [13]. The cross section obtained for the process (1) for $E_{\nu_e} = 40 MeV$ equals to $4.2\cdot10^{-40}$ cm^2 [12].

Alongside with charged current processes, the inelastic neutrino scattering, induced by neutral current:

$$\nu_e + {}^{56}Fe \rightarrow \nu_e' + {}^{56}Fe^*$$

should be taken into account. In the neutrino energy range of interest the inelastic scattering is determined, primary, by allowed transitions. The cross section of this reaction in the case of the initial nucleus ground state has the following form [14]:

$$\sigma^{NC}(E_\nu) = \frac{G_F^2 g_A^2}{\pi(2J_i+1)}(E_\nu - E_x)^2 \left|\left\langle f \left\| \sum_k \boldsymbol{\sigma}(k) t_0(k) \right\| i \right\rangle\right|^2 \tag{1}$$

Here G_F and g_A are the Fermi and axial vector coupling constants, respectively, E_ν is the energy of neutrino in the initial state, and E_x is the nucleus excitation energy. The square of the reduced matrix element

$$B(GT_0) = \frac{g_A^2 \left|\left\langle f \left\| \sum_k \boldsymbol{\sigma}(k) t_0(k) \right\| f \right\rangle\right|^2}{2J_i + 1}$$

governs the cross section dependence on the nuclear transition structure.

When calculating inelastic neutrino scattering on nuclei it is reasonable to deduce it in a model-independent way, basing on experimental results of nuclear structure investigations [15], for the currently available theoretical models may give substantial spread of nuclear matrix elements values. The same approach is useful in the double beta-decay theory, where information on corresponding nuclear matrix elements can be obtained from data on log *ft* for single beta-transitions and measurements of characteristics of charge-exchange reactions [16]. For ^{56}Fe the allowed transitions correspond to transitions from initial 0^+ to the final 1^+ - states, therefore estimations of matrix elements can be produced with the help of data on electromagnetic $M1$-strengths.

The processes of nuclear resonance fluorescence were investigated in [17]. Electromagnetic dipole transitions in ^{56}Fe were measured in photon-scattering experiments with a linearly polarized photon beam. In the case of $M1$ transitions the width of the excited 1^+ - state relatively to the transition on the nucleus ground state is determined by the following expression [18]:

$$\Gamma_0 = \frac{16\pi}{27}\frac{E_x^3}{\hbar^3 c^3} B(M1) \tag{2}$$

Here E_x is the excitation energy, B($M1$) – is the reduced probability of $M1$-transition. B($M1$) is written in the following form [18,19]:

$$B(M1) = \frac{3}{4\pi}\left|\left\langle f \left\| \sum_k [\mathbf{l}(k) t_0(k) + (\mu_S - 0.5)\frac{\boldsymbol{\sigma}(k)}{2} + \mu_V \boldsymbol{\sigma}(k) t_0(k) \right\| i \right\rangle\right|^2 \mu_N^2$$

Here μN is nuclear magneton, μ_S and μ_v are isoscalar and isovector nucleon magnetic moments, μ_S = 0.880, μ_v =4.706. As follows from the expression for B(M1), the isovector contribution to B(M1) exceeds significantly the isoscalar part. As for the orbital term, for pf-nuclei it is concentrated at excitation energies Ex ≤4 MeV, while for Ex in the range of 7-11 MeV, which is essential for neutrino registration, the determining factor is the spin contribution.

Consequently, for calculation of cross section in neutral channel $\sigma^{NC}(E_\nu)$, one can use the following relation, connecting $B(GT_0)$ and $B(M1)$:

$$B(GT_0) = \frac{4\pi g_A^2}{3\mu_V^2}\frac{B(M1)}{\mu_N^2}$$

From the values of μ_v =4.706 and g_A= -1.2761 it results:

$$B(GT_0) = 0.308\frac{B(M1)}{\mu_N^2} \tag{3}$$

Here it is taken into account, that for the $^{56}\mathrm{Fe}_{g.s.}$ J_i =0. The reduced transition probabilities $B(M1)$ can be found from (2) on the base of data on the widths Γ_0 of excited states of iron-56 nucleus. If Γ_0 is measured in meV and E_x in MeV, then

$$\frac{B(M1)}{\mu_N^2} = 0.2592\frac{\Gamma_0}{E_x^3} \tag{4}$$

As follows from (1), the cross section of inelastic neutrino-nucleus scattering is determined by the formula:

$$\sigma^{NC}(E_\nu) = 1.6862\cdot 10^{-44}(E_\nu - E_x)^2 B(GT_0)\ \mathrm{cm}^2 \tag{5}$$

Here E_ν , E_x are measured in MeV.

The investigation of dipole excitations of ^{56}Fe for the excitation energies E_x up to 9.8 MeV was performed in [17]. Twenty 1^+ – states with the total $B(M1)$ strength $\sum B(M1) = 4.31(18)\mu_N^2$ were examined. The reduced probabilities of electromagnetic $M1$ transitions $B(M1)$ are calculated with the help of data on the widths Γ_0 of these states, obtained in [20]. So, combining (3), (4), (5) it is possible to calculate the total cross section of inelastic neutrino scattering, caused by weak neutral current. The corresponding plot is presented in Fig. 1. Particularly, for E_ν=40 MeV $\sigma^{NC} = 22\cdot10^{-42}$ cm^2.

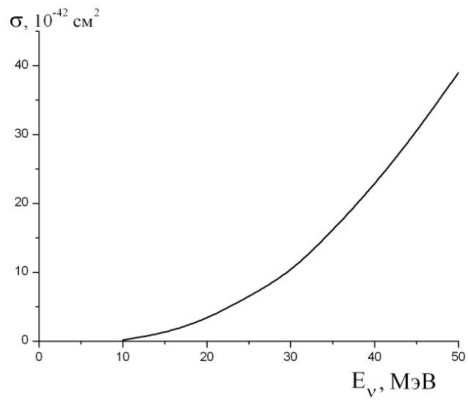

Fig1. *Dependence of neutrino – 56Fe inelastic scattering on neutrino energy.*

2.2. Interaction with ^{12}C

There are three channels of electron neutrino interaction with carbon, which is a part of the liquid scintillator $C_{10}H_{22}$.

Neutrino absorption, determined by charged current:

$$\nu_e + {}^{12}C \rightarrow {}^{12}N_{g.s.} + e^- \quad ; \qquad \text{CC} \qquad (6)$$

$$\nu_e + {}^{12}C \rightarrow {}^{12}N^* + e^- \qquad \text{CC.} \qquad (7)$$

Inelastic neutrino scattering, caused by neutral current:

$$\nu_e + {}^{12}C \rightarrow {}^{12}C^*(1^+, 1; 15.11 MeV) + \nu_2' \qquad \text{NC} \qquad (8)$$

All these interactions lead to creation of secondary particles, electrons and gamma-quanta, which can be registered by detector as neutrino signal. With the purpose to have benchmarks of the cross section orders it is worthwhile to refer to experimental results, obtained in KARMEN experiments for neutrino muon-decay-at-rest spectrum, with characteristic neutrino energy E_ν ~35 MeV. So, for reactions (6), (7) the experimental results are $9.1\cdot10^{-42}$ cm^2, $5.7\cdot10^{-42}$ cm^2 respectively. As for neutral current reaction (8), experimental result is a sum of cross sections both for ν_e and $\bar{\nu}_\mu$ inelastic scattering and equals to $10.1\cdot10^{-42}$ cm^2.

Theoretical calculations of reaction (6) cross section can be produced on the base of experimental data on log *ft* of $^{12}N_{g.s.}(\beta^+)^{12}C_{g.s.}$ transition. Reaction (7) is considered in [21] within the continuum random phase approximation. The cross section of neutrino neutral current excitation of 15.11 MV state in carbon can be obtained by the approach just the same as the one used for neutrino-iron inelastic scattering, taking into account the experimental rate of M1 γ-decay of 15.11 MeV state, Γ_γ =38.5 eV. The resulting sum of cross section values of (6), (7), (8) interactions equals to $20\cdot10^{-42}$cm^2.

2.3. Number of Signals

In the two-stage model the first neutrino pulse from SN1987A is connected with the initial stage of the collapse. For the total neutrino power in the first phase $W_{\nu_e} = 8.9 \cdot 10^{52}$ erg, neutrino energy 40 MeV and distance from Supernova to the Earth 50 kPs, the neutrino flux at the Earth surface is $0.5 \cdot 10^{10}$ 1/cm^2 [12]. The calculated cross sections values lead to one interaction for neutrino-carbon reaction and five interactions for electron neutrino with ^{56}Fe, that together with the registration efficiency of detector gives the event numbers, which coincide with the observed number of signals

3. Conclusion

LSD is a unique detector for observing the neutrino pulse connected with the first stage of collapse in the rotational mechanism scenario [8], because it is a detector which contains a sufficient mass of proper material for detecting, namely, the electron-neutrino pulse, but not only the antineutrino one (as was expected before). As to the other detectors, including hydrogen components (e.g., IMB type), they cannot detect a pulse consisting mainly of electron neutrinos. In the same way, the number of events detected in the neutrino–electron interaction, as is in the case of the KII detector, is small because of the smallness of the cross section in the supernova neutrino energy range ($\approx 10^{-43}$ cm^2) in comparison with the neutrino–^{56}Fe interaction.

Recently a number of works have been published [22 – 24], where the second neutrino pulse is connected with deconfinement process in compact stars. The investigations in this direction are very interesting.

On the first stage of the rotational collapse mechanism electron neutrino of high energy with $E_\nu \sim$ 40–50 MeV are generated. For their registration the use of great amounts of stable isotopes with large values of neutron excess *N-Z* is very promising.

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