Calculation of neutrino-nucleus cross section on the base of nuclear reactions data

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Abstract Calculation of neutrino–nuclei cross section is a question of considerable interest for neutrino detection, including solar, astrophysical and calibration neutrino experiments. Also it is an essential item for investigation of primary nucleosynthesis and searches for new physics in oscillations examination. Computations of cross sections for a number of nuclei, which are involved in setups for neutrino signal registration are presented.

Keywords: Neutrino Absorption Cross Section, Charge Exchange Reactions, Neutrino-Gallium Interaction

1. Introduction

Measurements of nuclear reaction characteristics, such as log ft values for electron capture or beta-decay processes, charge-exchange spectra, nuclear fluorescence intensities can give valuable information on nuclear structure necessary for model-independent neutrino-nuclei cross section computation. It can be shown that these qualities provide a possibility to obtain corresponding theoretical results, coinciding with the existing experimental data [1-7]. Here neutrino cross sections for a number of nuclei of interest are calculated.

2. Neutrino-Nuclei Interaction Cross Section

2.1. Neutrino interaction with ^{12}C

There are two experiments on direct measurement of neutrino-^{12}C interaction cross sections performed by KARMEN [1, 2, 5, 6] and LSND [3, 7] Collaborations. The neutrino sources are the positive muon decay at rest (DAR), monoenergetic muon neutrino beam, arising from stopped positive pion decay and muon neutrino flux, produced by positive pion decay in flight (DIF). As was shown in [8], the nuclear reactions data give a possibility to obtain the according nuclear matrix elements and calculate cross section for a number of neutrino-nuclei processes, induced by charged and neutral current. The corresponding results coincide with experimental values. Particularly the neutrino absorption cross section

$$\nu_e + {}^{12}C \rightarrow {}^{12}N_{g.s.} + e^- ,$$

averaged over electron neutrino DAR spectrum, was obtained. Its value is $9.1 \cdot 10^{-42}$ cm^2, which agrees with the measured one.

Also transition to excited states of nitrogen $^{12}N^*$, $^{12}C(\nu_e,e^-)^{12}N^*$, with μ^+ DAR ν_e beam was experimentally investigated [3,7]. The flux averaged cross section is

$\langle\sigma\rangle = (5.7 \pm 0.6_{star} \pm 0.6_{syst})\cdot 10^{-42}$ cm^2 [3], $\langle\sigma\rangle = (4.3 \pm 0.4_{star} \pm 0.6_{syst})\cdot 10^{-42}$ cm^2 [7]. As DAR neutrino spectrum is characterized by the mean energy E_ν~32 MeV, predominantly low multipoles give contribution to the cross section. Thus it can be assumed, that allowed Gamov-Teller transitions to excited 1^+ states of ^{12}N dominate. The low lying 1^+-state of ^{12}N, as it was found by the means of charge-exchange reactions, is E_x=3.57 MeV [9]. The expression for cross section has the following form:

$$\sigma_{GT}(E_\nu) = \frac{G_\beta^2 m_e^2}{\pi} g_A^2 B(GT)\pi_e\varepsilon_e F(Z_f, \varepsilon_e) \tag{1}$$

Here *B(GT)* is the square of Gamov-Teller nuclear matrix element for transition to a certain state of the final nucleus, divided by $(2J_i+1)$, g_A is the axial-vector interaction constant, $g_A = 1.2761$, ε_e and π_e are the energy and momentum of outgoing electron in units of m_e, $\varepsilon_e = (E_\nu-\Delta)/m_e$, Δ is the mass difference of the $^{12}N^*$ and ^{12}C nuclei and Fermi function $F(Z_f, \varepsilon_e)$ is the Coulomb correction function.

$$F(Z,\varepsilon,r) = 4(2pr)^{2(\gamma_0-1)} e^{\pi y} \frac{|\Gamma(\gamma_0+iy)|^2}{[\Gamma(2\gamma_0+1)]^2}$$

Here $\gamma_0 = [1 - (\alpha Z)^2]^{1/2}$, $y=\alpha Z\varepsilon/p$, r is the distance between electron and nucleus center. Averaging of $F(Z,\varepsilon,r)$ over nucleus volume should be performed. The method of $F(Z_f, \varepsilon_e)$ calculation is presented in [10]. If transition to E_x=3.57 MeV 1^+-state of ^{12}N constitutes a major part of the $^{12}C(\nu_e,e^-)^{12}N^*$ cross section, then *B(GT)* can be estimated according to (1). For $\langle\sigma\rangle = 5.7\cdot 10^{-42}$ cm^2 *B(GT)*=0.80. This result can be compared with $B(GT)_{g.s.}$, which corresponds to transition to the ground state of ^{12}N in $^{12}C(\nu_e,e^-)^{12}N_{g.s}$ reaction, $B(GT)_{g.s.} = 0.88$. The value *B(GT)*=0.80 can be used, under the assumption made, for estimation of $^{12}C(\nu_e,e^-)^{12}N^*$ cross section for meadow neutrino energies. Particularly, for $E_{\nu_e} = 40$ Mev $\sigma(E_{\nu_e}) = 9.5\cdot 10^{-42}$ cm^2.

2.2. Neutrino interaction with ^{71}Ga

Calculation of cross section of electron neutrino capture by ^{71}Ga nucleus,

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

is necessary for analysis of neutrino gallium-germanium experiments. The proposed project BEST [11] at Baksan Neutrino Observatory is aimed to searches for sterile neutrinos [12] on the base of calibration procedure with artificial neutrino sources. Thus estimation of ν_e-^{71}Ga cross sections for neutrino, produced by ^{51}Cr and ^{37}Ar is a question of interest.

The ground state of ^{71}Ga has quantum numbers $3/2^-$ and ^{71}Ge g.s. has $1/2^-$. Also for ^{51}Cr and ^{37}Ar artificial sources transitions to two low-lying excited states of ^{71}Ge are possible: $E_x = 0.175$ MeV, $5/2^-$ and $E_x = 0.500$ MeV, $3/2^-$. The recent precise measurements [13] lead to the following neutrino threshold energy for ^{71}Ga transition to the ground state of ^{71}Ge:

$$B(GT)_{g.s.} = 0.5\frac{D}{g_A^2 ft_{1/2}} \tag{2}$$

$$D = \frac{2\pi^3 \ln 2}{G_F^2 \cos^2 \vartheta_C m_e^5}$$

The fundamental constants values result in $D = 6288.6$ c. Here g_A is the axial-vector coupling constant, $g_A = -1.2755$ [16]. So, as follows from (2),

$$B(GT)_{g.s.} = 0.0864 \pm 0.0003 \tag{3}$$

Cross section calculations in terms of measurement [17], Q = 233.5 ± 1`.2 keV, were performed in [18]. The following values of log $ft_{1/2}$ and $B(GT)_{g.s}$ were obtained: log $ft_{1/2} = 4.353 \pm 0.005$, $B(GT)_{g.s.} = 0.086 \pm 0.001$.

Artificial sources ^{51}Cr and ^{37}Ar emit neutrinos with the following energies:

^{51}Cr – 0.427 MeV, 8.95 %; 0.432 MeV, 0.93%; 0.747 MeV, 81.63 %; 0.752 MeV,8.49%;

^{37}Ar – 0.811 MeV, 90.2%; 0.813 MeV, 9.8%.

According to (1), (3) the neutrino capture cross sections for transition to the ground state of ^{71}Ge can be calculated for ^{51}Cr and ^{37}Ar.

$$^{51}\mathrm{Cr}: \sigma_{g.s.} = (55.83 \pm 0.19)\cdot 10^{-46}\ \mathrm{cm}^2,$$

$$^{37}\mathrm{Ar}: \sigma_{g.s.} = (66.74 \pm 0.23\cdot 10^{-46}\ \mathrm{cm}^2$$

Contributions of excited states of ^{71}Ge, E_x=0.175 MeV and E_x=0.500 MeV, to the cross sections can be estimated from (^{3}He,t) charge exchange reaction [19]. The derived Gamov-Teller strengths are: E_x=0.175 MeV, $B(GT)$=0.0034(26); E_x=0.500 MeV, $B(GT)$=0.0176(14). It should be taken into account that these results are adjusted to $B(GT)_{gs}$= 0.0852, obtained from *ft* measurement [20]. Total cross sections of neutrino capture are as follows:

$$^{51}\mathrm{Cr}: \sigma_{tot} = (59.88 \pm 1.55)\cdot 10^{-46}\ \mathrm{cm}^2,$$

$$^{37}\mathrm{Ar}: \sigma_{tot} = (72.09 \pm 1.88)\cdot 10^{-46}\ \mathrm{cm}^2$$

These values are about one percent greater, than the results of [18], for lower energy threshold, Q=232.443±0.093 keV, is used. It will be observed, that certain problems, concerning $B(GT)$ extraction from the experiment should be considered. Just there are discrepancies between $B(GT)_{gs}$ magnitude, obtained from *ft* and (^{3}He,t) reaction for ^{100}Mo [21] and (p,n) reaction for ^{116}Cd [22]. Further increase of precision of charge-exchange reactions method is essential to matrix elements determination [23].

3. Conclusion

Determination of nuclear matrix elements by the model-independent method from experimental data gives a possibility to estimate cross sections of neutrino-nucleus processes. The calculated cross section values agree with the results of KARMEN and LSND experiments. Increase of precision of experiments on charge-exchange reactions should give exact results, necessary for interpretation of calibration experiments with neutrino. The model-independent method can be used for consideration of neutrino-nuclei interaction in different aspects of neutrino investigation.

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