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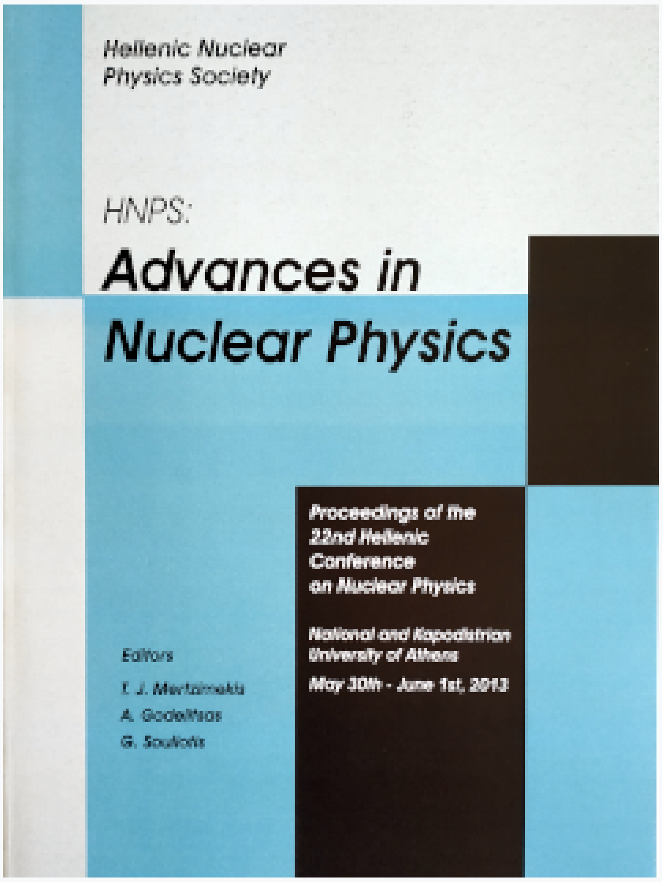

Studying the coherent channel of neutral current v-nucleus interaction

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Studying the coherent channel of neutral current ν-nucleus interaction

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Abstract

Original cross-sections calculations for neutral current neutrino scattering on ^{40}Ar isotope are performed in the context of the quasi-particle random phase approximation (QRPA) by utilizing realistic two-nucleon forces. The incoming neutrino energy range adopted, $\varepsilon_\nu \leq 100$ MeV, covers the supernova neutrinos, the low-energy beta-beam-neutrinos and the pion-muon stopped neutrino-beams existing or planned to be conducted at future neutron spallation sources. Subsequently, are the original cross sections convoluted with various supernova neutrino-energy distributions such as the two-parameter Fermi-Dirac and the power law distributions. The folded cross sections are obtained for various values of the parameters of these neutrino energy distributions corresponding to different supernova scenarios. One of the main purposes of this work is to explore the response of the ^{40}Ar isotope as supernova neutrino detector.

1. Introduction

The last few decades, the search of semi-leptonic weak processes involving lepton-nucleus interactions (neutrino-induced reactions on nuclei, β-decay modes, nuclear muon capture, etc.) has deepened our understanding on the fundamental electro-weak interactions and enriched our knowledge on nuclear structure and nuclear astrophysics [1]. Such precious information inspired significant probes within and beyond the standard electro-weak theory and offered valuable interpretations to experiments searching for neutrino detection and neutrino intrinsic properties (neutrino masses, neutrino oscillations, etc.) [2, 4]. Using nuclei as micro-laboratories in reactor, accelerator and underground neutrino production on detection experiments, neutrinos have been extensively investigated as key elementary particles in nuclear weak responses and in new astro-particle physics [5–7]. Nowadays, there are two new possibilities of measuring neutrino-nucleus cross-sections. The first, uses boosted β-decay radioactive nuclei as sources to produce neutrino-beams of low and intermediate energies (beta-beam neutrinos) [7]. The second possibility of measuring neutrino-nucleus cross sections is at stopped pion-muon neutrino facilities, existing (BooNe experiment) or expected to be built near spallation neutron sources (ORLaND experiment, European Spallation Source) [2].

The physics research that could be undertaken with the aforementioned neutrino-beam facilities is associated with the open questions in low and intermediate energy neutrinos in nuclear, particle physics and astrophysics. This research motivates a theoretical study of the advantages which carry various prominent nuclear regimes related to their use in neutrino experiments (COBRA, MOON, ICARUS, etc) [7] and to probe the structure of nucleons and nuclei [1–3, 7].

In this work we carry out extensive differential, total and cumulative cross sections calculations of (anti)neutrino scattering on ^{40}Ar isotope by employing the many-body nuclear wave functions produced within the $pp - nn$ quasi-particle random phase approximation (pp-nn QRPA) that utilizes realistic two-nucleon forces (the Bonn C-D potential). Our attention is focused on inelastic scattering (the elastic channel is rather simple to calculate) assuming that this nucleus, after its interaction with neutrinos goes to good quantum states of energies (E), angular momenta (J), parities (π) and other quantum numbers, so as the Donnelly-Walecka projection is applicable) [6].

2. Neutrino-nucleus Cross section calculations

The purpose of this work, is to perform detailed calculations for the cross sections of (anti)neutrino reactions with the isotope ^{40}Ar. At first we study the neutral current neutrino-nucleus reactions [6]

$$\nu_l(\widetilde{\nu}_l) + {}^{40}Ar \to {}^{40}Ar^* + \nu_l{}'(\widetilde{\nu}_l'), \tag{1}$$

where $\ell = e, \mu, \tau$. The cross sections are obtained within the context of the pp-nn quasi-particle RPA [4]. In the first stage, we determine the model parameters describing the nuclear structure of ^{40}Ar as follows.

The wave functions for the final states $|J_f^\pi\rangle$ of the nucleus ^{40}Ar entering the description of the interactions of Eq. (1), are very important for the cross section calculations. Their reliability has been checked by the reproduction of the low-lying excitation spectrum ($\omega \preceq 4$ MeV) of ^{40}Ar induced by the neutrinos (antineutrinos) of the reaction. We used as model space the 10 lower energy levels up to $N = 3\hbar\omega$, i.e. the major shells with 0, 1, 2, 3 ($\hbar\omega$).

The pairing strength parameters for proton pairs, g^p_{pair}, and neutron pairs g^n_{pair} have been adjusted so as the semi-empirical pairing gaps denoted as $\Delta^{exp}_{p,n}$, to be reproduced. We found that, there is a very good agreement between the empirical energy gaps for neutrons, Δ^{exp}_n, and for protons, Δ^{exp}_p, with the corresponding theoretical lowest quasiparticle energy which had been determined by using the well known three-point formula [6, 7].

As it is well known, after applying a multipole analysis on the weak hadronic current, as in the Donnelly-Walecka method, the neutral-current (anti)neutrino-nucleus differential cross section is written as

$$\frac{\mathrm{d}^2\sigma_{i\to f}}{\mathrm{d}\Omega\mathrm{d}\omega}\Big|_{\nu/\tilde{\nu}} = \frac{2G^2\varepsilon_f^2}{\pi(2J_i+1)}\left(\sum_{J=0}^{\infty}\sigma^J_{CL} + \sum_{J=1}^{\infty}\sigma^J_T\right) \tag{2}$$

(G_F is the weak interaction coupling constant). In the latter equation, the first summation over σ^J_{CL} contains the contributions of the Coulomb $\widehat{\mathcal{M}}_J$ and longitudinal $\widehat{\mathcal{L}}_J$ operators given by the expression

$$\sigma^J_{CL} = cos^2\frac{\theta}{2}\,|\langle J_f\|\widehat{\mathcal{M}}_J(q) + \frac{\omega}{q}\widehat{\mathcal{L}}_J(q)\|J_i\rangle|^2\,. \tag{3}$$

The second summation over σ^J_T contains the contributions coming from the transverse electric $\widehat{\mathcal{T}}^{el}_J$ and transverse magnetic $\widehat{\mathcal{T}}^{mag}_J$ multipole operators written as

$$\begin{aligned}\sigma^J_T &= \left(-\frac{q_\mu^2}{2q^2}cos^2\frac{\theta}{2} + sin^2\frac{\theta}{2}\right)\left[|\langle J_f\|\widehat{\mathcal{T}}^{mag}_j(q)\|J_i\rangle|^2 + |\langle J_f||\widehat{\mathcal{T}}^{el}_j(q)||J_i\rangle|^2\right] \\ &\mp 2sin\frac{\theta}{2}\sqrt{-\frac{q_\mu^2}{2q^2}cos^2\frac{\theta}{2} + sin^2\frac{\theta}{2}}\sum_{J=1}^{\infty}\Re e\langle J_f||\widehat{\mathcal{T}}^{mag}_J(q)||J_i\rangle\langle J_f||\widehat{\mathcal{T}}^{el}_J(q)||J_i\rangle^*\,.\end{aligned} \tag{4}$$

For the explanation of the various parameters entering Eq. (4) see Refs. [6, 7]. The differential cross section (as a function of the neutrino energy ε_ν) for the coherent neutrino-nucleus scattering, can be cast in the form [2, 3, 6]

$$\sigma_{coh} = \frac{1}{16}\sigma_0\left(\frac{\varepsilon_\nu}{m_ec^2}\right)^2 A^2[1 - \frac{Z}{A} + (4\sin^2\theta_w - 1)\frac{Z}{A}]^2\,, \tag{5}$$

where $\sigma_0 = 4{G_F}^2(m_ec^2)^2/[\pi(\hbar c)^4] = 1.705\times10^{-44}cm^2$ (θ_w denoting the Weinberg angle). The signal in the ν-nucleus coherent scattering is the nuclear recoil energy. The maximum recoil kinetic energy is given by [2]

$$T_{max} = \frac{2\varepsilon_\nu^2}{M_A + 2\varepsilon_\nu}\,, \tag{6}$$

where M_A is the mass of the target nucleus.

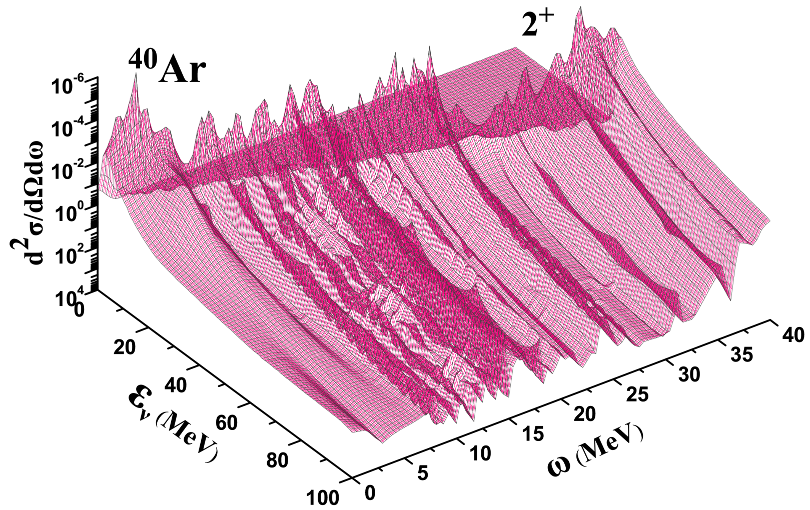

Figure 1: The double differential cross section, $d^2\sigma/d\Omega d\omega$ as function of the excitation energy ω of the nucleus and the scattering angle θ, for ^{40}Ar. The curves correspond to $J^\pi = 2^+$ multipole states [6].

3. Results

Figure 1 shows the variation of double differential cross-section $\frac{\mathrm{d}^2\sigma_{i\rightarrow f}}{\mathrm{d}\Omega\mathrm{d}\omega}$ as a function of the excitation energy of the nucleus ω and the scattering angle θ of the outgoing lepton, for ^{40}Ar. For all excitation energies ω in the range $0 < \omega < 25 - 30$ MeV, the cross-section is clearly backward peaked ($\theta \approx 180°$), a result that comes from the contribution of the transverse terms of the neutrino ^{40}Ar interaction.

The folded cross sections for ^{40}Ar are illustrated in Fig. 2. These results have been obtained by folding the original cross sections with a Fermi-Dirac distribution [7]. More specifically, Fig. 2 shows the energy dependence of the folded differential cross section $[d\sigma(\omega)/d\omega]_{fold}$ for the different supernova neutrino scenarios described by Fermi-Dirac distributions with (i) T =5.17 MeV, η_{dg}=2.7 and (ii) T= 6.20 MeV, η_{dg}=2.7.

4. Summary

In the present work, we used the microscopic approach of the pp-nn quasi-particle RPA to evaluate cross sections for the neutral current reaction $^{40}Ar(\nu, \nu')^{40}Ar^*$. We started from double differential cross sections, $d^2\sigma/d\Omega d\omega$, calculated (state-by-state) with the QRPA and, subsequently we obtained integrated $d\sigma/d\omega(\omega)$ and total σ_{tot} cross sections. These cross sections are folded with the neutrino-energy distributions of specific neutrino sources as the Fermi-Dirac and power-law distributions corresponding to various supernova neutrino scenarios.

The present results show that ^{40}Ar present rich responses in the excitation energy range $\omega \leq 20$ MeV (including transitions to bound states $\omega \leq 10 MeV$), relevant for solar neutrinos, reactor neutrinos, and geo-neutrinos but also for the low- and intermediate-energy supernova neutrinos [8]. The inelastic neutrino nucleus cross sections are suitable for use in astrophysical neutrino (including supernova neutrinos) simulations utilized in order to interpret neutrino oscillations, neutrino properties and supernova explosion mechanisms.

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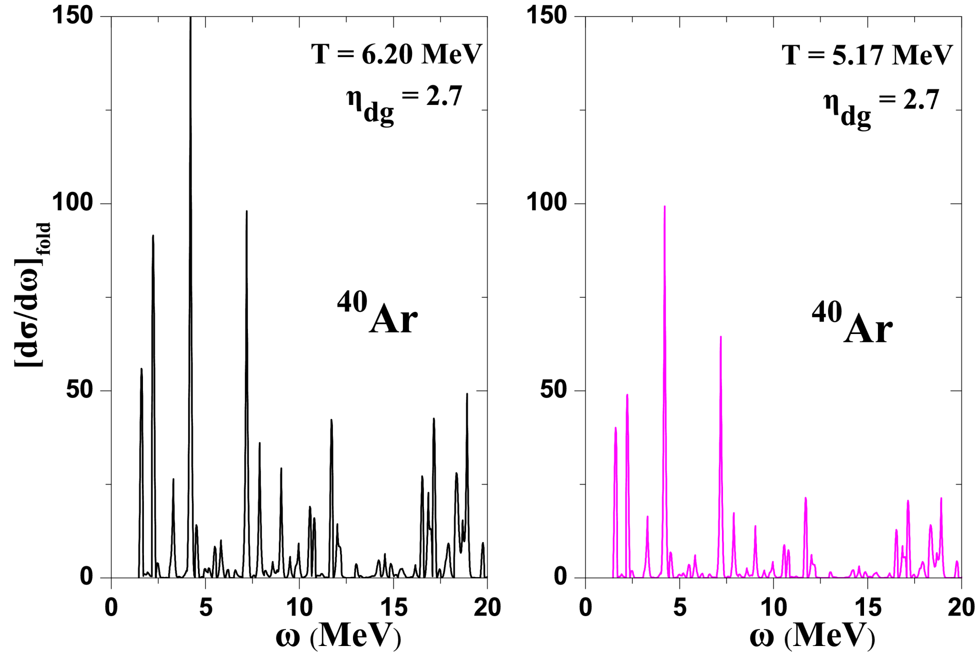

Figure 2: Differential cross section for the reaction $^{40}Ar(\nu,\nu')^{40}Ar^{*}$, averaged over neutrinos and antineutrinos and over a Fermi-Dirac distribution with temperatures T =5.17 and 6.20 MeV. The corresponding degeneracy parameter is η_{dg}=2.7.

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