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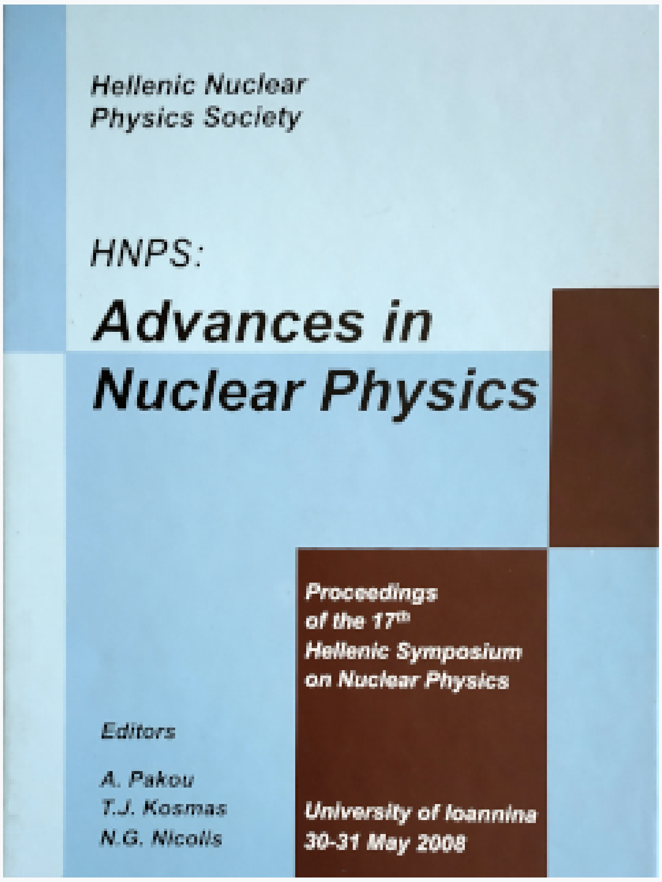

Coherent and incoherent channels of neutrino-nucleus reactions

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Coherent and incoherent channels of neutrino-nucleus reactions

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Abstract

Inelastic neutrino-nucleus scattering cross sections at low and intermediate energies are investigated for currently interesting nuclei employed in neutrino-detection experiments. This is an extension to charged current processes of our previous QRPA calculations referred to neutral current neutrino/antineutrino-nucleus reactions. Our preliminary results for the reactions ^{56}Fe$(\nu_e, e^-)^{56}$Co and ^{40}Ar$(\nu_e, e^-)^{40}$K compare rather well with similar calculations obtained in the context of continuum RPA.

Key words: Neutrino-nucleus reactions; Inelastic cross sections; Quasi-particle random phase approximation; Supernova neutrinos; Solar neutrinos
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1 Introduction

Neutrino studies are an interesting research topic in nuclear, astronuclear physics and cosmology. Neutrinos are sensitive probes for investigating astroparticle processes and stellar evolution [1,3], e.g. solar neutrinos provide important information on astronuclear processes and matter densities inside the sun, while supernova neutrinos are useful for studying supernova explosions and neutrino properties [4–6]. On the other hand, nuclear systems have extensively used as micro-laboratories in neutrino studies (through charged- and neutral current neutrino-nucleus processes involving vector and axial-vector weak interactions) for investigating fundamental interactions and elementary particles. Nuclear responses for neutrinos are crucial for studies of the low and intermediate energy neutrinos through the neutrino-nucleus weak processes [5,6].

Experimental searches of neutrinos in nuclear and particle physics, due to the fact that neutrino processes themselves are very weak and rare processes, involve necessarily highly precise measurements for stringent verification of the standard electro-weak theory and testing several theories beyond the standard model. Consequently, proper selections and arrangements of the nuclear weak processes are important for neutrino studies in nuclear micro-laboratories. We mention that, low-energy neutrinos are studied by using the charged- and neutral-current interactions with protons and deuterons as well as with many nuclei [1,3]. Recent neutrino detection experiments, in addition to charged current processes, can take advantage of the neutral current neutrino-nucleus interaction and either measure explicit transitions of the final nucleus or detect the nuclear recoil (coherent processes) [1]. In particular, the neutral-current interaction with deuterons is very powerful probe in the SNO detector. Also, neutrinos produced by accelerators are used to study neutrino oscillations and nuclear weak responses [1].

The neutrino-nucleus reactions offer significant probes to detect or distinguish the neutrinos of several flavors and to study the basic structure of the weak interactions. In particular, several terrestrial experiments, being in operation or planed to operate for the detection of astrophysical neutrinos (solar, supernova, etc.), are good sources of information for the properties of neutrinos and the evolution of stars [1,2].

In the present work, we examine the role of ^{56}Fe and ^{40}Ar nuclei as neutrino detectors by calculating their charge current neutrino-induced reaction cross sections at low and intermediate energies ($0 \leq \epsilon_i \leq 100$ MeV) of the incoming neutrino.

2 Brief description of the formalism

In the present work we consider charged current neutrino-nucleus interactions in which a low or intermediate energy neutrino (or antineutrino) is scattered inelastically from a nucleus (A,Z). Obviously, there is only incoherent channel in these charged current processes. The initial nucleus is assumed to be spherically symmetric having ground state a $|J^\pi\rangle = |0^+\rangle$ state.

The corresponding standard model effective Hamiltonian in current-current interaction form is written as

$$\mathcal{H} = \frac{G \cos\theta_c}{\sqrt{2}} j_\mu(\mathbf{x}) J^\mu(\mathbf{x}), \qquad (1)$$

where $G = 1.1664 \times 10^{-5} GeV^{-2}$ is the weak coupling constant. j_μ and J^μ denote the leptonic and hadronic currents, respectively. According to V-A theory, the leptonic current takes the form

$$j_\mu = \bar{\psi}_{\nu_\ell}(x)\gamma_\mu(1-\gamma_5)\psi_{\nu_\ell}(x). \tag{2}$$

where ψ_{ν_ℓ} are the neutrino/antineutrino spinors.

The structure of the hadronic current describing the charged current processes (neglecting second class currents and pseudo-scalar contributions) is written as

$$J_\mu = \bar{\Psi}_N \left[F_1\gamma_\mu + F_2 \frac{i\sigma_{\mu\nu}q^\nu}{2M} + F_A\gamma_\mu\gamma_5 \right] \tau_c \Psi_N, \quad c = +, - \tag{3}$$

(M stands for the nucleon mass and Ψ_N denote the nucleon spinors). F_i, $i = 1, 2$ represent the weak nucleon form factors given in terms of the well known charge and electromagnetic form factors (CVC-theory) for proton (F_i^p) and neutron (F_i^n) by the expressions

$$F_1 = \frac{1}{2}\left[F_1^p - F_1^n\right] \qquad\qquad F_2 = \frac{1}{2}\left[F_2^p - F_2^n\right] \tag{4}$$

F_A stands for the axial-vector form factor for which we employ the dipole ansatz given by

$$F_A = -\frac{1}{2} g_A \left(1 - q^2/M_A^2\right)^{-2} \tag{5}$$

where $M_A = 1.05$ GeV, is the dipole mass, and $g_A = 1.258$, is the static value (at $q = 0$) of the axial form factor.

In the convention we used in the present work q^2, the square of the momentum transfer, is written as

$$q^2 = q^\mu q_\mu = \omega^2 - \mathbf{q^2} = (\varepsilon_i - \varepsilon_f)^2 - (\mathbf{p}_i - \mathbf{p}_f)^2 \tag{6}$$

where $\omega = \varepsilon_i - \varepsilon_f$ is the excitation energy of the nucleus. ε_i denotes the energy of the incoming and ε_f that of the outgoing neutrino. $\mathbf{p}_i$, $\mathbf{p}_f$ are the corresponding 3-momenta of the incoming and outgoing neutrino/antineutrino, respectively.

The charged-current neutrino-nucleus differential cross section, after applying a multipole analysis of the weak hadronic current as in Donnelly-Walecka-Haxton method [10,15,16], is written as

$$\frac{\mathrm{d}^2\sigma_{i\to f}}{\mathrm{d}\Omega\mathrm{d}\omega} = \frac{G^2}{\pi}\frac{|\vec{k}_f|\varepsilon_f}{(2J_i+1)}F(Z,\varepsilon_f)\left(\sum_{J=0}^{\infty}\sigma_{CL}^J + \sum_{J=1}^{\infty}\sigma_T^J\right) . \tag{7}$$

The summations in Eq. (7) contain the contributions σ_{CL}^J, for the Coulomb $\widehat{\mathcal{M}}_J$ and longitudinal $\widehat{\mathcal{L}}_J$, and σ_T^J, for the transverse electric $\widehat{\mathcal{T}}_J^{el}$ and magnetic $\widehat{\mathcal{T}}_J^{mag}$ multipole operators defined as in Ref. [10,15,16]. These operators include both polar-vector and axial-vector weak interaction components. The Fermi function $F(Z,\varepsilon_f)$ takes into account the Coulomb-final-state interaction between the studied nucleus and the outgoing final lepton (electron). In the present work we treat this interaction relativistically in the same manner as outlined in Ref. [11].

3 The QRPA for charged current reactions

For charge current neutrino-nucleus induced reactions, the wave functions for the initial and final nuclear states can be constructed in the context of the pn QRPA [13]. In this method, the m^{th} excited state with total angular momentum J projection M and parity π, denoted by $|J_m^\pi M\rangle$, is created by acting on the QRPA ground state with the phononoperator

$$\hat{Q}^{m\dagger}_{J^\pi M} = \sum_{k,l}\Big[\, X^m(kl,J)A^\dagger(kl,JM) + Y^m(kl,J)\tilde{A}(kl,JM)\,\Big] \tag{8}$$

where X, Y are the forward and backward going amplitudes which can be determined from the QRPA matrix equation, see, e.g., Ref. [9]. The quasi-particle pair creation and annihilation operators $A^\dagger$, $\tilde{A}$ are defined as

$$A^\dagger(kl,JM) \equiv \left[a_k^\dagger a_l^\dagger\right]_M^J = \sum_{m_k,m_l}\langle j_k m_k j_l m_l|JM\rangle a^\dagger_{km_k}a^\dagger_{lm_l} \tag{9}$$

$$\tilde{A}(kl,JM) = (-1)^{J-M}A(kl,J-M)\,. \tag{10}$$

Above, the square brackets denote angular-momentum coupling while $a^\dagger$ and a denote quasi-particle creation and annihilation operators. In neutral-current processes the index τ equals with 1 for neutrino-proton interactions and -1 for neutrino-neutron interactions respectively.

The next step in using QRPA is the construction of the eigenvalue problem (QRPA equations) which reads

$$\begin{pmatrix} \mathcal{A} & \mathcal{B} \\ -\mathcal{B} & -\mathcal{A} \end{pmatrix} \begin{pmatrix} X^m \\ Y^m \end{pmatrix} = \Omega^m_{J^\pi} \begin{pmatrix} X^m \\ Y^m \end{pmatrix}, \tag{11}$$

where $\Omega^m_{J^\pi}$ denotes the excitation energy of the nuclear state $|J^\pi_m\rangle$. The QRPA-matrices $\mathcal{A}$ and $\mathcal{B}$, are deduced by the matrix elements of the double commutators of $A^\dagger$ and A with the nuclear hamiltonian $\hat{H}$ defined as

$$\mathcal{A}_J(\tau k, l; \tau' k', l') = \langle 0^+_{RPA} | [A_\tau(k, l, J, M), [\hat{H}, A^\dagger_{\tau'}(k', l', J, M)]] | 0^+_{RPA} \rangle, \tag{12}$$

$$\mathcal{B}_J(\tau k, l; \tau' k', l') = \langle 0^+_{RPA} | [A_\tau(k, l, J, M), [\tilde{A}_{\tau'}(k', l', J, M), \hat{H}]] | 0^+_{RPA} \rangle \tag{13}$$

Our nuclear hamiltonian $\hat{H}$ includes as field interaction a Coulomb corrected Woods-Saxon potential and as two-body residual interaction the Bonn-C potential. The indices k, l in Eqs. (8)-(13) run over the single particle levels of our model space which consists of twelve active single particle levels up to $4\hbar\omega$ major harmonic oscillator shells. We note that, the particle conservation is separately checked for protons and neutrons.

4 Results and discussion

In the present work, we present realistic state-by-state calculations for inelastic neutrino-nucleus scattering processes. We mainly focus on charged current processes of neutrinos with ^{56}Fe and ^{40}Ar nuclei. The strong pairing interaction between the nucleons was treated in the framework of the BCS theory. Within this theory, one can adjust the pairing force in order to obtain realistic quasiparticle energies. In the present case this was done separately for protons and neutrons. The adjustment was done by enforcing the lowest quasiparticle energy to match the phenomenological pairing gaps $\Delta_{n/p}$ (for neutrons and protons). These gaps are given by various phenomenological expressions. In our present work we employ the linear approximation [7].

$$\Delta_n(^A_Z X) = -\frac{1}{4}[S_n(^{A+1}_Z X) - 2S_n(^A_Z X) + S_n(^{A-1}_Z X)], \tag{14}$$

$$\Delta_p(^A_Z X) = -\frac{1}{4}[S_p(^{A+1}_{Z+1} X) - 2S_p(^A_Z X) + S_p(^{A-1}_{Z-1} X)] \,. \tag{15}$$

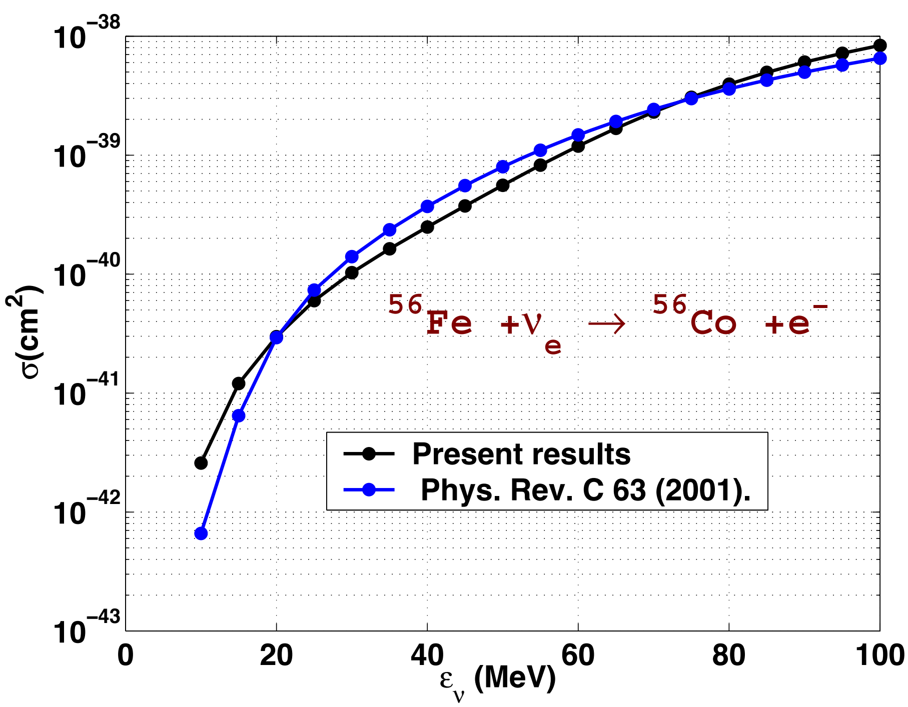
in which $^A_Z X$ stands for the doubly-even nucleus under consideration. The separation energies $S_{n/p}$ are provided, e.g., by [8].

Having fixed the pairing-interaction strengths, the only parameters of our method left are those of the QRPA. In the QRPA level the strength parameters for the particle-hole channel, g_{ph} and the particle-particle channel, g_{pp} originated from the solutions of the QRPA-equations were fixed so as the lowest lying energies to be reproduced [14]. We mention that the determination of these strength parameters was achieved separately for each set of multiple states with spin J and parity π. The excitation spectra, i.e. the set of phonons of the doubly even nuclei were formed by diagonalising the QRPA matrices in two quasiparticle approximation. The resulting spectrum relies on the calculations done with the adjusted Woods-Saxon potential for obtaining the single-particle energies.

In this work we study two charged current neutrino-nucleus processes. Both of these reactions have previously been studied theoretically by using continuum RPA.

(i) The first process we study is the charged current reaction of ^{56}Fe with electron neutrinos described by

$$^{56}Fe + \nu_e \longrightarrow ^{56}Co + e^- \qquad (16)$$



a)

Fig. 1. Differential cross sections, for the dominant sets of multipole states in the reaction ^{56}Fe$(\nu_e, e^-)^{56}$Co.

The importance of this reaction has been studied by many authors [1,4,5,16]. In Fig. 1 we illustrate the preliminary results obtained in this work for the differential cross section. For comparison the results of Ref. [5] obtained with continuum RPA are also shown. We notice that for such small values the agreement is good.

(ii) The second process we study here is the charged current reaction of ^{40}Ar with electron neutrinos (see Refs. [17–20]), i.e.

$$^{40}Ar + \nu_e \longrightarrow ^{40}K + e^- \tag{17}$$

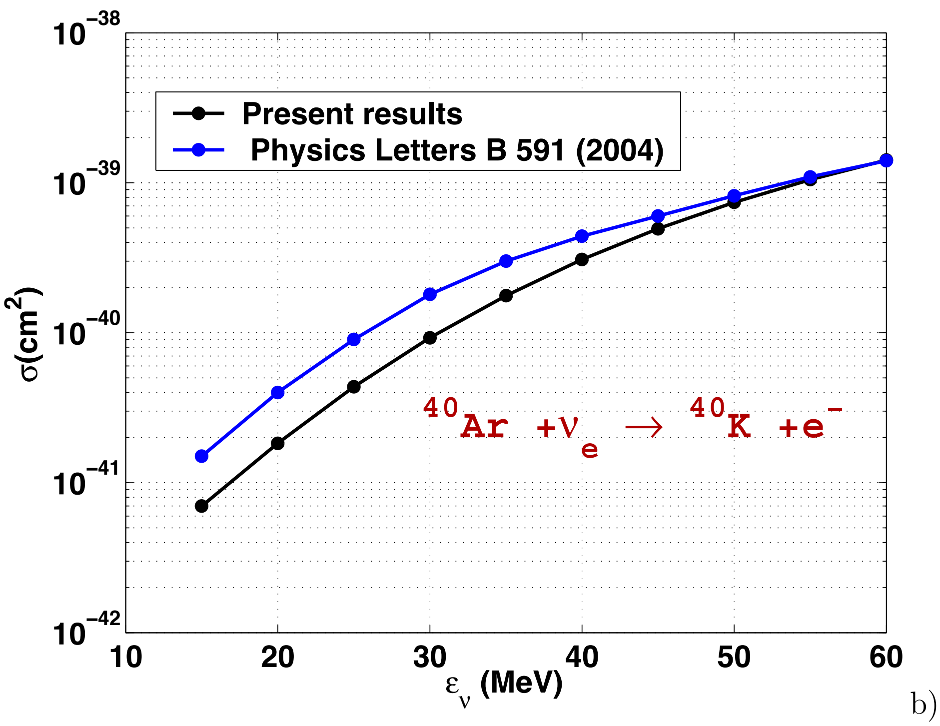


Fig. 2. Differential cross sections, for the dominant sets of multipole states in the reaction ^{40}Ar$(\nu_e, e^-)^{40}$K.

5 Summary and Conclusions

Using QRPA, we performed state-by-state calculations for coherent and incoherent electron neutrinonucleus charged current processes (J-projected states) for currently interesting nuclei like ^{56}Fe and ^{40}Ar. For low incoming-neutrino energies ($\varepsilon_i \leq 15 - 20$ MeV), i.e. for solar neutrino energies only the coherent channel is important (neutral current processes). For higher energies both channels are significant. Our preliminary results in the studied charged current processes ^{56}Fe$(\nu_e, e^-)^{56}$Co and ^{40}Ar$(\nu_e, e^-)^{40}$K are in good agreement with similar calculations using continuum RPA.

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