Neutral current reaction cross sections for the stable $^{100}$Mo isotope

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Abstract. Motivated by the ongoing MOON neutrino experiment at Japan aiming to search for double beta and neutrinoless double beta decay events, we investigate inelastic neutrino scattering cross sections for the stable $^{100}$Mo isotope by performing state-by-state calculations. The required many body nuclear wave functions are constructed within the context of the quasi-particle random phase approximation (QRPA) tested in the reproducibility of the low-lying spectrum of the $^{100}$Mo isotope.

1. Introduction

Current experiments searching for low-energy neutrinos and rare event processes are significant sources of information for the fundamental weak interactions, the nuclear structure, the neutrino properties and the astro-nuclear physics. The MOON (Molybdenum Observatory Of Neutrinos) is a modern next generation neutrino experiment mainly aiming to search for double-beta and neutrinoless double-beta decay events. MOON is also sensitive to low-energy solar neutrinos above the $^{100}$Mo beta-decay threshold of 168 keV and it has the capability of addressing multiple physics question within a single detector [1, 2].

The MOON experiment provides real time sensitivity to charged current neutrino-nucleus reactions. Its large reaction rates for all solar neutrino sources are due to the low threshold energy and the large Gamow-Teller strengths for the ground and excited states of the produced $^{100}$Tc nucleus.

In the present work, we investigate inelastic cross sections of the neutral current reaction $^{100}Mo(\nu, \nu')^{100}Mo^*$ at low incoming-neutrino energies ($\epsilon_i \leq 100$ MeV). This enables us to explore the role of this isotope as low-energy neutrino detector (solar, supernova neutrinos, etc.).

2. The QRPA method for neutral current reactions

For neutral current neutrino-nucleus reactions, the wave functions for the initial and final nuclear states can be constructed within the quasi-particle RPA where the $m^{th}$ excited state of a multipolarity $|J_m^\pi M\rangle$ ($J =$ total angular momentum, $M =$ projection and $\pi =$ parity) is created by acting on the QRPA ground state with the phonon operator

$$\hat{Q}^\dagger_{Jm} = \sum_{k \leq l} \left[ X^m_{\tau}(kl, J) \hat{A}^\dagger_{\tau}(kl, JM) + Y^m_{\tau}(kl, J) \hat{A}_{\tau}(kl, JM) \right], \quad (1)$$
$X$ and $Y$ are the forward and backward going amplitudes determined by the QRPA matrix equations. The quasi-particle pair creation and annihilation operators $A^\dagger$, $A$ are defined as

$$A^\dagger_{\tau}(kl, JM) \equiv (1 + \delta_{kl})^{-\frac{1}{2}} \left[ a^\dagger_{\tau(kl)} a^\dagger_{\tau(M)} \right]^J_{JM}$$

$$\tilde{A}_{\tau}(kl, JM) = (-1)^{J-M} A^\dagger_{\tau}(kl, J-M) \tag{2}$$

where $a^\dagger$ ($a$) the creation (annihilation) quasi-particle operators. The next step in using QRPA is the construction of the eigenvalue problem (QRPA matrix equations) which reads

$$\begin{pmatrix} A & B \\ -B & -A \end{pmatrix} \begin{pmatrix} X^m \\ Y^m \end{pmatrix} = \Omega^m_{\pi} \begin{pmatrix} X^m \\ Y^m \end{pmatrix}, \tag{3}$$

where $\Omega^m_{\pi}$ denotes the excitation energy of the nuclear state $|J^m\pi\rangle$. The QRPA matrices $A$, $B$ contain matrix elements of the double commutators of $A^\dagger$, $A$ with the Hamiltonian operator $H$.

3. Results

In the present work we perform realistic state-by-state calculations for all inelastic neutrino-nucleus channels by using the quasi-particle RPA method [3, 4]. We calculated both Fermi and Gamow-Teller type contributions of the polar vector and axial vector operators. Our method has been checked in the reproducibility of the low-lying spectrum of the $^{100}$Mo isotope by using:

(i) at the BCS level the pairing parameters for proton-pairs $g^p_{\text{pair}}$, and neutron-pairs $g^n_{\text{pair}}$, and

(ii) at the QRPA level the fitting parameters for the strength of the residual interaction, i.e. the $g_{ph}$, for the particle-hole, and the $g_{pp}$, for the particle-particle channel, respectively.

The model space used consists of the following eleven active single particle levels: $0f^{7/2}$, $1p^{3/2}$, $1d^{1/2}$, $0f^{5/2}$, $0g^{9/2}$, $1d^{5/2}$, $2s^{1/2}$, $1d^{3/2}$, $0g^{7/2}$, $0h^{11/2}$, $0h^{9/2}$, for which the corresponding single-particle energies were produced by a Coulomb corrected Woods-Saxon potential.

In Fig. 1 we show the calculated cross sections for neutrino scattering off the $^{100}$Mo isotope as a function of the incoming neutrino energy, $\epsilon_i$. More specifically, in Fig. 1 (left side) the differential cross sections for the dominant multipole states 0+, 1+, 2+, 3+, 4+, 5- and 6+ are shown. These cross sections resulted from the original double differential ones $d^2\sigma/d\Omega d\epsilon_f$ by summing over the individual contributions of each multipole state. The curve labeled ”total” corresponds to the sum over the differential cross sections $d\sigma/d\Omega$ originating from all $J^\pi$ multipole states (essentially up to $J^\pi = 6$). As can be seen, the contribution of the 0+ and 1+ multipoles dominate the total differential cross section $d\sigma/d\Omega$.

In the right side of Fig. 1, the latter differential cross sections are plotted for various values of the scattering angle $\theta$ (step $\Delta \theta = 15^\circ$, for $0^\circ \leq \theta \leq 180^\circ$) of the reaction $^{100}$Mo$(\nu, \nu')^{100}$Mo*.

These plots show clearly that, for low neutrino energies ($\epsilon_i \leq 10 - 12$ MeV) the differential cross section decreases as the scattering angle increases, but for higher energies the cross section increases with the scattering angle. By using the above differential cross sections and numerical integration techniques we could obtain the total cross section $\sigma_{\text{tot}}(\epsilon_i)$ [3, 4].

Our calculated cross sections show a smooth increase similar to that of the cross sections obtained for the charged current reaction

$$\nu_e + ^{100}\text{Mo} \rightarrow e^- + ^{100}\text{Tc} \tag{4}$$

by the MOON experiment group [1, 2].

The results of the cross sections calculated in the present work are useful for investigating the response of the $^{100}$Mo isotope as a neutrino detector. At the neutrino energies of Fig. 1 one could extract information about the response of $^{100}$Mo isotope to solar and supernova neutrinos.

Closing we mention that there exists a number of detectors having the ability to study neutrino events and detect either the charged-current processes (through the produced electrons or positrons) or the neutral current reaction (mostly through the emitted neutrons, protons or $a$-particles). For the charge-exchange process (4) the $^{100}$Mo isotope has a threshold (Q value) of only Q= 0.17 MeV [2].
Figure 1. Differential cross sections $d\sigma/d\Omega$ with respect to the initial neutrino energy, $\epsilon_i$ for the reaction $^{100}\text{Mo}(\nu,\nu')^{100}\text{Mo}^*$ illustrating: (i) the dominant multipolarities for scattering angle $\Phi = 15^\circ$ (left), and (ii) the angular dependence by increasing the scattering angle by a step $\Delta \theta = 15^\circ$, for $0^\circ \leq \theta \leq 180^\circ$ (right).

4. Summary and Conclusions
$^{100}\text{Mo}$ isotope is used for real-time spectroscopic studies of the individual solar neutrino sources, as well as for studying supernova neutrino and double beta decay processes. We have investigated neutral current reaction cross sections at low and intermediate energies of the reaction $^{100}\text{Mo}(\nu,\nu')^{100}\text{Mo}^*$. We have performed systematic calculations for all the even-even Mo isotopes [5] and we plan to calculate charged current cross sections in order to support the MOON experiment from a theoretical point of view.

5. Acknowledgments
This research was supported by the ΠΕΝΕ∆ Νο 03Ε∆807 project of the General Secretariat for Research and Technology of the Hellenic Ministry of Development. One of us (TSK) acknowledges support from the ILIAS EU Project.

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