The nuclear response of terrestrial detectors to low-energy neutrino spectra

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Abstract. In current probes searching for rare-event processes, appropriate nuclear targets are employed. In this work the response of such detectors to various low-energy neutrino spectra is explored starting from state-by-state calculations of the neutrino-nucleus reactions cross sections obtained by using the quasi particle random phase approximation (QRPA) based on realistic two-body residual interactions.

1. Introduction

During the last few decades, the search of semi-leptonic weak processes involving lepton-nucleus interactions (β-decay modes, neutrino-induced reactions on nuclei, nuclear muon capture, etc.) has deepened our knowledge on the fundamental electro-weak interactions and enriched our understanding on nuclear structure [1, 2, 3]. Such precious information inspired significant probes within and beyond the standard electro-weak theory and provided valuable interpretations to various experiments like those looking for neutrino masses, neutrino oscillations, neutrino detection, etc. [2, 4]. Using nuclei as micro-laboratories in reactor, accelerator and underground neutrino production/detection experiments, neutrinos have been extensively studied as key elementary particles in nuclear weak responses and in new physics beyond the standard model [2, 4, 5].

Recently, terrestrial neutrino experiments (combined with measurements of neutrino telescopes) have provided crucial information about the weak processes taking place in the interior of stars and showed that neutrinos are extremely sensitive probes for studying stellar evolution and astro-nuclear processes [4, 6]. To this end, measurements of solar neutrinos (at KAMLAND, Borexino, etc.) used to test the standard solar model (SSM) while recent probes at SNO (SNO+ experiment) aim to measure low-flux solar neutrinos (pep and CNO-cycle neutrinos) to check the abundances of solar core and clarify if the metalicity in the Sun is homogeneous [5]. Furthermore, recent stellar evolutions models describing the explosion mechanism of type II supernovae have provided us with important information regarding the role of neutrinos in the evolution of massive stars, explosive nucleo-synthesis, etc. [4, 6, 7].

During the collapse and explosion phase neutrino-nucleus reactions play an interesting role for supernova nucleosynthesis. However, uncertainties on astrophysical interactions of neutrinos and supernova physics opened numerous questions that are still unanswered and the degree of this knowledge is limited by our understanding of the neutrino-nucleus cross sections. Also, projected neutrino experiments need good control over systematic errors originating from neutrino-nucleus cross section uncertainties at low and intermediate nuclear excitation energies.
2. Low-energy neutrino-nucleus probes

As is well known, neutrinos excite nuclear modes not accessible to the electromagnetic probes that allow the study of the characteristics of the nuclear dynamics and of the nuclear interaction usually hidden in other processes. Thus, inelastic scattering of neutrinos on nuclei may induce nuclear excitations below or above particle emission thresholds. The latter excitations might subsequently decay via particle emission, thus, contributing to nucleosynthesis in the interior of stars [6, 7]. These processes could be incorporated into nuclear networks of explosive nucleosynthesis when the cross sections for neutrino-induced reactions like

\[ (A, Z) + \nu \rightarrow \nu' + X + a , \]  

where \((A, Z)\) and \(X\) are the target and daughter nucleus, respectively, and \(a\) the emitted light particle (it may be a proton, a neutron or an a-particle), are reliably estimated. Such reactions may be considered as two-step processes in the compound nucleus picture as: (i) the target nucleus is excited via the neutral current neutrino-nucleus reaction

\[ (A, Z) + \nu \rightarrow \nu' + (A, Z)^* \]  

and (ii) the compound nucleus then decays into the particle channels, where the relevant decay rates might be taken from a statistical model (e.g. a conventional Hauser-Feshbach model) [2].

Focusing on the neutrino-nucleus probes, they are not only important in our efforts to better understand the nature of reactions like the above, but also they are significant in the current experimental studies of low and intermediate energy neutrinos. Nowadays, the study of neutrino scattering off nuclei is motivated by the interest to know how the nuclear medium affects the nucleon axial current and probe the structure of the nucleons (e.g. to study the strangeness content of the nucleon) and nuclei [1, 8]. The importance of the neutrino-nucleus interaction probes is not limited to the neutrino detection, but it is also related to the study of the processes generating them, and to their scattering inside matter (earth, stars, supernovae).

Recently, it became feasible to detect low-rate (solar and supernova) neutrinos by measuring the recoiling nucleus with very-low threshold-energy gaseous-detectors. Such studies are in conjunction with the direct-detection of cold dark matter (CDM) events and double beta decay measurements [2, 5]. Among the various ongoing or proposed double beta decay detectors, the molybdenum and the Cd-based semiconductor detectors CdTe and CdZnTe (they are currently employed for various rare processes in several areas of physics) have proposed to be used in the MOON and COBRA experiments, respectively, as detectors of double beta decay processes [5]. Since the response of such materials as neutrino (solar, supernova, etc.) detectors have not been addressed up to the present, a systematic study of neutrino–nucleus reaction cross sections (folded with various neutrino energy spectra) for their stable isotopes is needed [9, 10].

3. Nuclear detector response to low-energy neutrino sources

In general, nuclear responses to neutrinos are crucial for low-energy neutrino studies in nuclei that include the vector and the axial-vector weak interactions. Accordingly, the nuclear responses connected to the charged current neutrino-nucleus interactions are nuclear isospin and spin isospin responses, which reflect the spin isospin structures. Such responses in nuclear medium are modified much by strong nuclear spin and isospin interactions [2]. Isospin and spin isospin giant resonances, which absorb most of isospin and spin isospin strengths, are located at the excitation region of \(E_{\text{ex}} = 10 - 25\) MeV. Thus, nuclei show large responses for neutrinos in that energy region. In the case of the neutral current neutrino-nucleus reactions, in addition to the other neutrino-induced nuclear excitations, the coherent channel \((g.s. \rightarrow g.s.\) transitions) is also possible and, as has been shown [9], this is the dominant channel for low-energy neutrinos.
From a nuclear theory point of view, up to now neutrino-nucleus cross sections have been investigated for various nuclear isotopes by employing several methods, such as: (i) Closure approximation within the shell model and the random phase approximation (RPA) to calculate the average contribution of the transitions to all excited states of the target nucleus (inclusive processes). (ii) Relativistic or non-relativistic Fermi gas methods utilizing a Lindhard function to compute the sum of all partial rates of the inelastic neutrino-nucleus reaction channels [1]. The incoherent rate is evaluated by integrating over a continuum of the excited states of a local Fermi sea. (iii) State-by-state calculations by using shell model or continuum RPA versions [6] for the explicit construction of the final nuclear states. Such calculations are reliable for low neutrino energies in nuclei where the transitions to definite nuclear states (ground-state or some low-lying excitations) could be dominant.

Recently, an advantageous numerical approach has been constructed for nuclear structure calculations based on analytic expressions of the reduced matrix elements of all the basic tensor operators that allow the systematic calculation of multi-pole matrix elements by separating out the geometrical coefficients from the kinematical parameters (energy, momentum, scattering angle) of the studied reaction. This method improves over other previous methods employing multi-pole expansion procedure in nuclear structure calculations. It is applicable in nuclear systems where the initial and final nuclear states have good quantum numbers of energy (E), angular momentum (J) parity (\(\pi\)) and isospin (T) so as the multipole expansion of the Donnelly-Walecka method is reliable [9].

In the present work, we perform extensive calculations of the differential and integrated cross sections of the neutrino-nucleus reactions for the isotopes contained in the COBRA double beta decay detector mentioned before. The many-body nuclear matrix elements are evaluated in the context of the quasi-particle random phase approximation (QRPA) by utilizing the advantageous numerical approach constructed in Ref. [9]. It is worth mentioning that, our QRPA method is based on realistic two-body forces and has been successfully used in other semi-leptonic nuclear processes. It offers a relatively simple and detailed state-by-state calculation of all the individual low-lying excitations induced by the interaction of neutrinos with nuclei [9].

Since our main purposes is to explore the response of the COBRA isotopes as solar and supernova neutrino detectors, we subsequently convolute the original neutrino-nucleus cross sections with appropriate neutrino-energy distributions (for supernova such distributions are the two-parameter Fermi-Dirac, the Power-Law, etc. distributions [10]) in order to obtain folded differential, cumulative and total cross sections for various values of the parameters entering the aforementioned energy distributions.

Closing, it must be stressed that, from a nuclear theory point of view, it is important to compute the transition matrix elements entering the neutrino-nucleus reactions cross sections and other observables with accurate many-body nuclear wave functions based on realistic two-body forces, a task extremely difficult due to the fact that neutrino-nucleus cross sections are highly suppressed in neutrino-detection experiments [9, 10].

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