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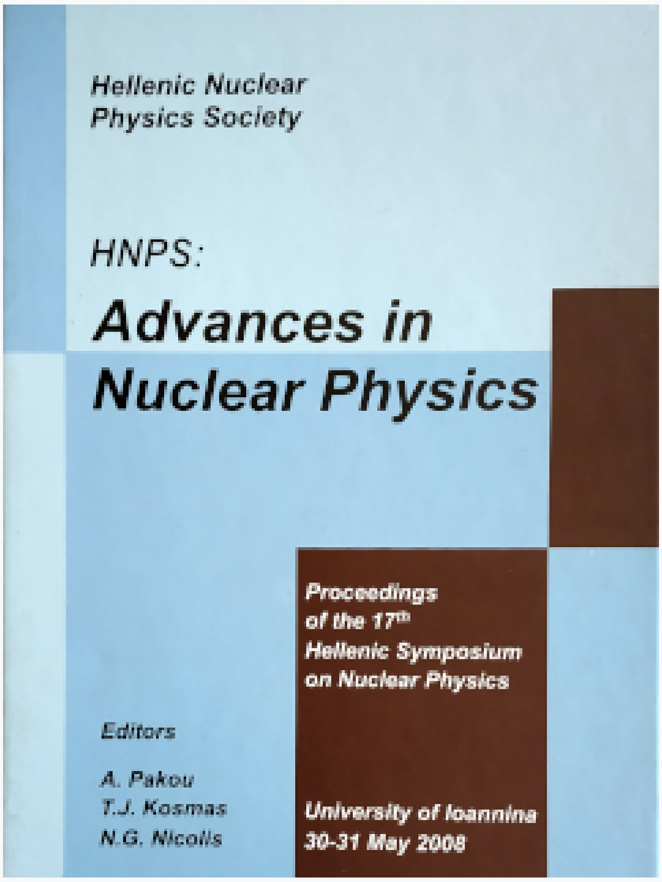

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Using the folding method for studying the nuclear response to Supernova neutrino spectra

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Abstract

The folding (convolution) method is applied to explore the response of some nuclear detectors to the energy-spectra of supernova neutrinos. In the first step, double differential cross sections as well integrated and total ones are calculated in the context of the quasi particle random phase approximation (QRPA). These cross section values are subsequently, folded with a specific neutrino-energy distributions to find the nuclear responses we are interested in. Due to the fact that neutrino-nucleus interactions are very weak, the evaluated cross sections are extremely small ($10^{-42} cm^2$). Thus, one needs a very fine convolution tool to obtain accurate description of the nuclear responses to various neutrino energy-spectra (supernova, laboratory, e.t.c.).

1 Introduction

Neutrinos are extremely significant probes to provide detailed information about the evolutions of stars at far distances[1,2]. They also provide general information about the structure and properties of the weak interactions, as they are only interacting via the weak forces with matter. Weak physics and neutrino-interactions are widely regarded as central players in the explosion mechanism. The core of the star is so hot and dense that even the neutrinos are trapped. These neutrinos scatter out of the core on a timescale of about ten seconds, taking away with them the vast majority of the gravitational binding energy released in the collapse.As neutrinos only participate in weak interaction processes and cross sections for scattering reactions involving neutrinos are very small, the importance of neutrinos to astrophysical processes has long been underestimated [4]. However, models describing the explosion mechanism of type II supernovae provide an important role for neutrinos in these processes. As it is well known, neutron star a flux of 10^{58} neutrinos is emitted during the cooling of a newly formed, representing approximately 99% of the total released energy.

Although the neutrinos are only weakly interacting, this enormous amount of particles and energy traveling through the different layers of the star is able to cause a considerable transformation of the elements synthesized during the thermonuclear burning processes in the life of the star. The supernova neutrinos play an important role in explosive nucleosynthesis processes, causing a considerable transformation of the material synthesized during the hydrostatic burning phases in the life of the star. In the present work, we focus on the investigation of supernova detection by terrestrial experiment. In particular, we are going to study the nuclear response to supernova neutrino detection spectra of the Mo isotopes. To this end, the required differential cross sections are provided through realistic state-by-state calculations (performed within the context of the quasi particle random phase approximation (QRPA))[7].The specific neutrino-energy distributions for the supernova neutrino spectra are employed [3]and the convolution procedure is followed.The shape of the neutrino energy-distribution is provided by astrophysical searches and is the well known Fermi-Dirac distribution [2,5].

2 Formalism for neutrino-nucleus folded differential cross sections

As mentioned in the Introduction, a very interesting neutrino source in current astro-particle physics studies is the supernova explosion which produces an enormous number of neutrinos.During a supernova explosion, all six flavor neutrinos, ν_e, $\tilde{\nu}_e$, ν_μ, $\tilde{\nu}_\mu$, ν_τ, and $\tilde{\nu}_\tau$, are produced. Among them, ν_e decouples and escapes at the largest radius via the charged- and the neutral-current interactions with matter. Then, the temperature of ν_e is about 3.5 MeV. On the other hand, $\tilde{\nu}_e$ decouples at a little inner region than ν_e, since the proton density relevant to $\tilde{\nu}_e$ is less than the neutron one. Therefore, $\tilde{\nu}_e$ has the higher temperature of around 5 MeV. The other neutrinos decouple at the sphere with the highest temperature of around 8 MeV. As the cross sections are roughly proportional to the square of the incoming neutrino energy, the higher temperature μ and τ neutrinos and neutral-current reactions will dominate nucleosynthesis processes. Numerical simulations on supernova neutrino dynamics have shown [2] that the energy-spectra of supernova neutrinos could be well described by a two-parameter Fermi-Dirac distribution of the form

$$f_\nu(E_\nu, T, \alpha) = N_2(\alpha)\,\frac{1}{T^3}\frac{E_\nu^2}{1+e^{(E_\nu/T+\alpha)}}\,, \qquad (1)$$

where T is the neutrino temperature and α parameter associated with the non-zero chemical potential. $N_2(\alpha)$ denotes the normalization factor given from

$$\frac{1}{N_n(\alpha)} = \int_0^\infty \frac{x^n}{e^{(x-\alpha)}+1} dx \, , \tag{2}$$

for n=2. The average neutrino energy $\langle E_\nu \rangle$ can be written in terms of the functions of Eq. (2) as [6]

$$\langle E_\nu \rangle = \frac{N_2(\alpha)}{N_3(\alpha)} T = (3.1515 + 0.125\alpha + 0.0429\alpha^2 + ...)T \tag{3}$$

Thus, for a given value of the degeneracy parameter α, the neutrino temperature T is fixed by using the relation between average neutrino energy $\langle E_\nu \rangle$ and T given in Eq. (3). The numerical simulation studies predict the average energies for various flavors of neutrinos to be $\langle E_{\nu_e} \rangle \approx 10 - 11 MeV$, $\langle E_{\tilde{\nu}_e} \rangle \approx 15 - 16 MeV$, $\langle E_{\nu_x} \rangle \approx 23 - 25 MeV$ [5,6,3]. In the neutral-current neutrino-nucleus processes we consider in the present work, low and intermediate energy neutrinos (or antineutrinos) with initial four-momentum ε_f $(\mathbf{k}_f)$ are elastically or inelastically scattered from a nucleus (A,Z) via the exchange of neutral Z^0 bosons. Such a reaction is represented by

$$\nu + (A, Z) \longrightarrow \nu' + (A, Z)^* \tag{4}$$

where ν or $(\nu^{'})$ denote neutrinos and anti-neutrinos of any flavor. The nucleus is supposed to be spherically symmetric and in its ground state $|J_i^{\pi_i}\rangle = 0^+$. After the reaction,the nucleus is left in an excited state with final parity and angular momentum J_f, π_f. Using natural units $\hbar = c = 1$), the differential cross section is then given by

$$\left(\frac{\mathrm{d}^2\sigma_{i\to f}}{\mathrm{d}\Omega \mathrm{d}\omega}\right)_{\nu/\bar{\nu}} = (2\pi)^4 \kappa_f \varepsilon_f \sum_{s_f, s_i} \frac{1}{(2J_i+1)} \sum_{M_f, M_i} |\langle f|\hat{H}_W|i\rangle|^2 \tag{5}$$

where $\hat{H}_W$ is the weak interaction Hamiltonian which is produced by the current-current interaction hypothesis and M_f, M_i the magnetic quantum numbers of J_f and J_i.

In order to estimate the response of a nucleus to a specific source of neutrinos, the calculated differential cross sections of neutrino-nucleus induced reactions must be folded with the neutrino energy distribution of the source in question. In the case of differential neutrino-nucleus cross sections, $d\sigma(E_\nu, \omega)/d\Omega$, the folding is defined by the expression

$$\frac{d\sigma(\omega)}{d\Omega} = \int_{\omega}^{\infty} \frac{d\sigma(E_\nu,\omega)}{d\Omega} f_\nu(E_\nu) dE_\nu \,, \tag{6}$$

where $\omega = \varepsilon_i - \varepsilon_f$ denotes the excitation energy of the nucleus, with ε_i the energy of the incoming neutrino, while ε_f ($\mathbf{k}_f$) represent the energy (momentum) of the outgoing lepton. Moreover, being intrinsically polarized and coupling to the axial vector as well as to the vector part of the hadronic current, neutrinos are able to reveal other and more precise nuclear structure information than, e.g. charged particles $(\mu, e, p, e.t.c)$ do. The most important problem in extracting information from neutrino-nucleus scattering experiments remains the very small interaction cross sections. These restrictions become rather unimportant when considering astrophysical processes as is the case in our present work.

3 Results and discussion

In this work we have studied folded differential cross sections for ^{98}Mo isotope.This is an isotope contained in the MOON experiment planed for neutrino observation at Japan. By using the results for the differential cross sections obtained previously with QRPA method [7] and Eq. (6) we calculated the folded differential cross sections. We studied systematically the angular and initial-neutrino energy dependence of the folded differential cross sections of the neutral - current reaction reaction $^{98}Mo(\nu,\nu')^{98}Mo^*$, for initial neutrino energies in the range $\varepsilon_i \leq 100$ MeV and for various values of the scattering angle Φ (step $\Delta\Phi = 15^o$). We considered various values of neutrino temperature T at the source and chemical potential (degeneracy parameter) α. The preliminary results are shown in Figs.1-2. More specifically,in Fig.1 the angular dependence of the folded differential cross section is illustrated for Φ ranging between $0^o \leq \Phi \leq 180^o$ and for temperature and degeneracy parameter values: $T = 4MeV$ and $\alpha = 0, 3$. In Fig.2 we show the angular dependence of the folded differential cross section for the same range of the scattering angle and for temperature and degeneracy parameter values $T = 5MeV$ and $\alpha = 0, 3$.

We see that, the folded differential cross sections increase with the scattering angle of the incoming neutrino. For for incoming neutrino energy $E_v \approx 33MeV$ the nuclear response becomes maximum. Also we notice that the folded differential cross sections increase appreciably as the degeneracy parameter α changes $\alpha = 0$ to $\alpha = 0$. The same behavior is shown with increasing the temperature T.

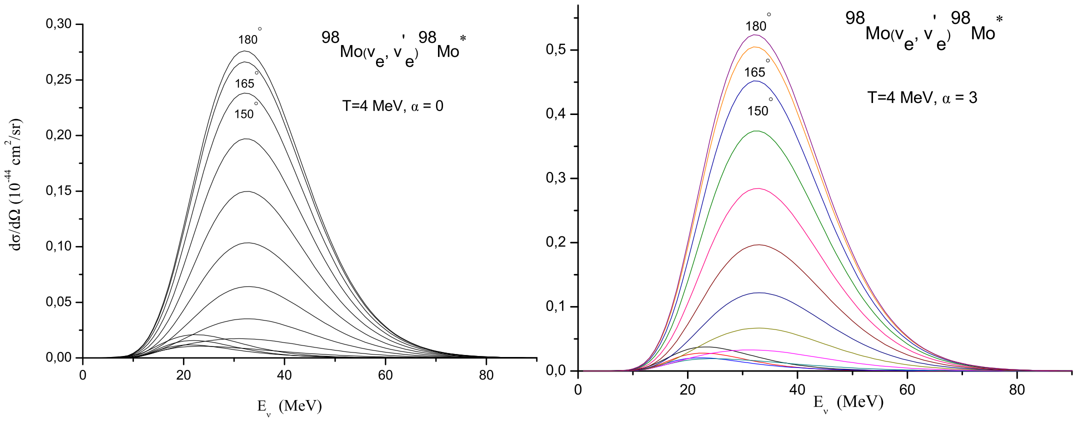

Fig. 1. Integrated folded differential cross sections for the neutral-current reaction $^{98}Mo(\nu,\nu')^{98}Mo^*$ averaged over Fermi - Dirac distribution with $T = 4MeV and = 0,3$. Results are given for scattering angles between 0^o and 180^o, in 15^o steps.

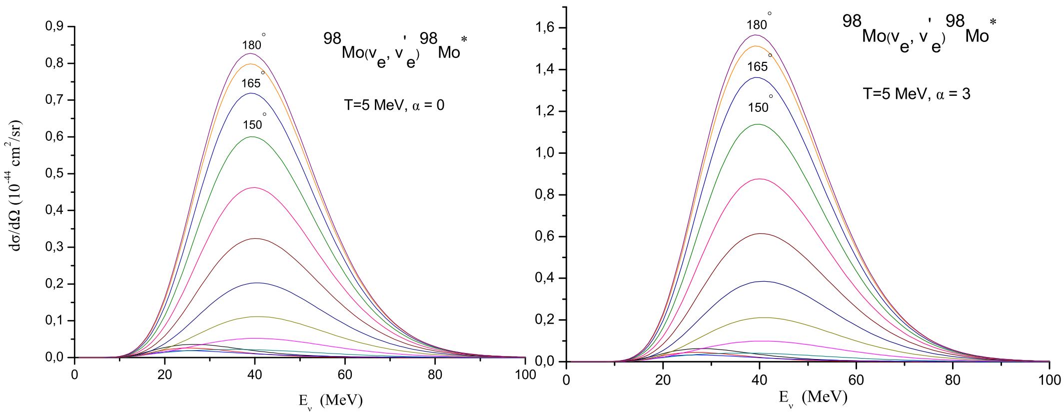

Fig. 2. Integrated folded differential cross sections for the neutral-current reaction $^{98}Mo(\nu,\nu')^{98}Mo^*$ averaged over Fermi - Dirac distribution with $T = 5MeV and = 0,3$. Results are given for scattering angles between 0^o and 180^o, in 15^o steps.

4 Summary and Conclusions

In the present work, we have studied the response of ^{98}Mo isotope to SN-neutrino spectra for the range of Temperatures: $T = 4,5MeV$ and degeneracy-parameter α values: $0,3$ by evaluating the folded differential cross-sections $d\sigma/d\Omega$ for neutral current reaction $^{98}Mo(\nu,\nu')^{98}Mo^*$. We used the convolution method and employed Fermi-Dirac neutrino energy distribution which is appropriate for neutrinos produced by a Supernova explosion. Currently we study the response of other Mo-isotopes to supernova neutrino spectra. We are working on improving the convolution method by concentrating on the involved numerical integration and interpolation as well as on adopting appropriate fast convolution techniques.

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