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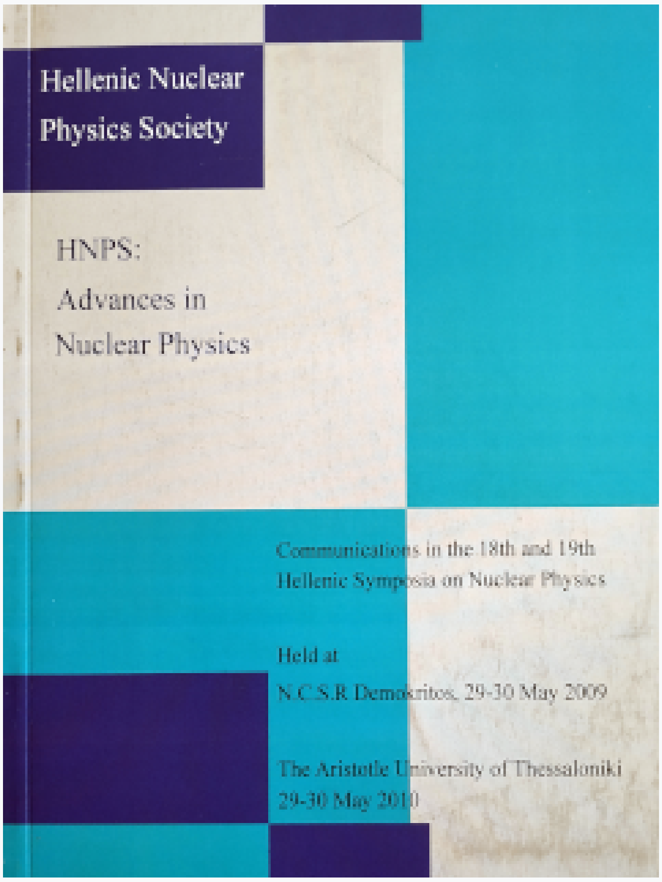

Nuclear response to supernova neutrino spectra

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Nuclear response to supernova neutrino spectra

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Abstract

In current probes searching for rare event processes, appropriate nuclear targets are employed (in the COBRA double-beta decay detector the CdZnTe semiconductor is used). 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. As a concrete example, we examine the response of ^{64}Zn isotope to low energy supernova neutrinos.

Key words: Neutrino-nucleus reactions, Supernovae.
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1 Introduction

In general, nuclear responses to neutrinos are crucial for low-energy neutrino detection but also for nuclear structure studies because of the presence of both 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 modifed much by strong nuclear spin and isospin interactions [1,2]. Isospin and spin isospin giant resonances, which absorb most of isospin and spin isospin strengths, are located at the excitation region of E_{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 (gs $\rightarrow$ gs transitions) is also possible and, this is the dominant channel for low-energy neutrinos.

In the present work, we study nuclear responses to supernova neutrino spectra using the convolution method and the neutrino energy distributions described in Section 2.

2 Nuclear detector response to low-energy neutrino sources

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 [3,4].

For the double differential cross sections, $d^2\sigma(\varepsilon_\nu, \theta, \omega)/d\Omega d\omega$, of neutrino-nucleus reactions, the folding is defined by the expression

$$\left[\frac{d^2\sigma(\theta,\omega)}{d\Omega d\omega}\right]_{folded} = \int_{\omega}^{\infty} \frac{d^2\sigma(\varepsilon_\nu,\theta,\omega)}{d\Omega d\omega}\eta(\varepsilon_\nu)d\varepsilon_\nu\,, \tag{1}$$

where $\eta(\varepsilon_\nu)$ represents the energy distribution of SN-neutrinos (traditionally a Fermi-Dirac or Power-Law distributions are utilized) [5,6].

If we introduce the chemical potential n_{dg}, the Fermi-Dirac energy distribution reads

$$\eta_{FD}[\varepsilon_\nu, T, n_{dg}] = F(n_{dg})\,\frac{1}{T^3}\frac{\varepsilon_\nu^2}{1+e^{(\varepsilon_\nu/T-n_{dg})}}\,, \tag{2}$$

In this case the width of the spectrum is reduced compared to the corresponding thermal spectrum (for this reason the parameter n_{dg} is also called pinching parameter). (in MeV) is the neutrino temperature. The degeneracy parameter n_{dg}, is the ratio of the chemical potential divided by the temperature. The factor $F_2(n_{dg})$, is the normalization constant of the distribution determined so that

$$\int_0^\infty n_{FD}[\varepsilon_\nu, T, n_{dg}]d\varepsilon_\nu = 1\,. \tag{3}$$

This means that the normalization constant $F(n_{dg})$ depends on the degeneracy parameter n_{dg} and it is given by the relation

$$\frac{1}{F(n_{dg})} \equiv \int_0^\infty \frac{x^2}{e^{x-n_{dg}}+1} dx \,. \tag{4}$$

The mean energy, $\langle \varepsilon_\nu \rangle$, of the neutrino is written as a function of temperature as [7]

$$\langle \varepsilon_\nu \rangle = (3.1515 + 0.125\; n_{dg} + 0.0249\; {n_{dg}}^2 + ...)T \,. \tag{5}$$

We can easily prove that, for $n_{dg} = 0$, $F(0) = \frac{7\pi^4}{120} \sim 5.68$. Also, inserting Eq. (4) into Eq. (2), we take

$$\eta_{FD}[\varepsilon_\nu, T, n_{dg}] = \left[\int_0^\infty \frac{x^2}{e^{x-n_{dg}}+1} dx \right]^{-1} \frac{(\varepsilon_\nu^2/T^3)}{1+e^{(\varepsilon_\nu/T - n_{dg})}} \,. \tag{6}$$

After processing the later equation is written as

$$\eta_{FD}[\varepsilon_\nu, T, n_{dg}] = \frac{1}{\int_0^\infty \frac{x^2}{e^x + e^{n_{dg}}} dx} \frac{(\varepsilon_\nu^2/T^3)}{e^{(\varepsilon_\nu/T)} + e^{n_\alpha}} \,. \tag{7}$$

From the later equation it is clear that, for $n_{dg} = -\infty$ we finally take

$$\begin{aligned} \eta_{FD}[\varepsilon_\nu, T, n_{dg} = -\infty] &= (\varepsilon_\nu^2/T^3) e^{-(\varepsilon_\nu/T)} \left[\int_0^\infty x^2 e^{-x} dx \right]^{-1} \\ &= \frac{1}{2}\, (\varepsilon_\nu^2/T^3) e^{-(\varepsilon_\nu/T)} \,. \end{aligned} \tag{8}$$

It had been found that [5], the SN-neutrino energy spectra can be fitted by using a Power-Law energy distribution of the form:

$$\eta_{PL}[\langle \varepsilon_\nu \rangle, \alpha] = C \left(\frac{\varepsilon_\nu}{\langle \varepsilon_\nu \rangle} \right)^\alpha e^{-(\alpha+1)(\varepsilon_\nu/\langle \varepsilon_\nu \rangle)} \,, \tag{9}$$

where $\langle \varepsilon_\nu \rangle$ is the neutrino mean energy and the parameter α adjusts the width of the spectrum. The normalization factor C, is calculated by the equation

$$\int_0^\infty \eta_{PL}[\langle \varepsilon_\nu \rangle, \alpha] d\varepsilon_\nu = C \int_0^\infty \left(\frac{\varepsilon_\nu}{\langle \varepsilon_\nu \rangle} \right)^\alpha e^{-(\alpha+1)(\varepsilon_\nu/\langle \varepsilon_\nu \rangle)} d\varepsilon_\nu \; = 1 \,. \tag{10}$$

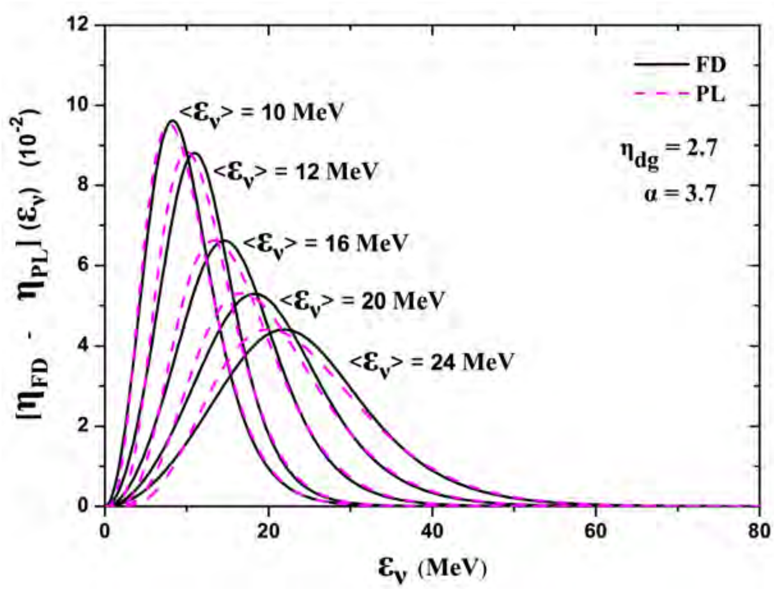

Fig. 1. Comparison between Fermi-Dirac and Power-law energy distributions for various values of their parameters.

From the later equation we find

$$C = \frac{(\alpha+1)^{\alpha+1}}{\Gamma(\alpha+1)\langle\varepsilon_\nu\rangle}\,, \tag{11}$$

therefore, Eq. (9) becomes

$$\eta_{PL}[\langle\varepsilon_\nu\rangle, \alpha] = \frac{(\alpha+1)^{\alpha+1}}{\Gamma(\alpha+1)}\,\frac{\varepsilon_\nu^\alpha}{\langle E\rangle^{\alpha+1}} e^{-(\alpha+1)(\varepsilon_\nu/\langle\varepsilon_\nu\rangle)}\,. \tag{12}$$

For $\alpha = 2$, Eq. (12) gives

$$\eta_{PL}[\langle\varepsilon_\nu\rangle, \alpha = 2] = \frac{27}{2}\,\frac{\varepsilon_\nu^2}{\langle\varepsilon_\nu\rangle^3} e^{-3\varepsilon_\nu/\langle\varepsilon_\nu\rangle}\,. \tag{13}$$

By comparing Eqs. (9) and (13), we conclude that, the equality (equivalent spectra) applies when the temperature of the neutrinosphere and its mean energy $\langle\varepsilon_\nu\rangle$, related via the expression

$$T = \frac{\langle\varepsilon_\nu\rangle}{3}. \tag{14}$$

We note that, for non-degenerate particles $\langle\varepsilon_\nu\rangle = 3$, which means that, the above equality between the distributions applies when we consider the neutrinos non-degenerate [5,6].

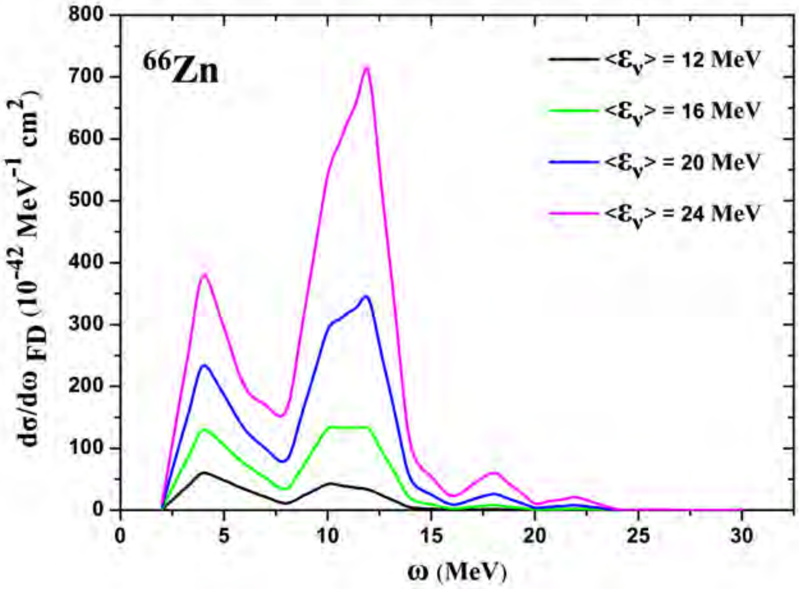

Fig. 2. Differential cross section for the reaction $^{66}Zn(\nu,\nu')^{66}Zn^{*}$, averaged over neutrinos and antineutrinos and over a Fermi- Dirac distribution with mean energies $\langle\varepsilon_\nu\rangle$=12, 16, 20 and 24 MeV.

3 Results and discussion

The folded results for ^{66}Zn are illustrated in Fig. 2. These results have been obtained by folding the original cross sections with a Fermi-Dirac distribution. More specifically, Fig. 2 shows the mean energy dependence of the folded differential cross section $[d\sigma(\omega)/d\omega]_{fold}$ for η_{dg}=2.7 (the mean energy values used are $\langle\varepsilon_\nu\rangle$=12, 16, 20 and 24 MeV).

We see that, the folded differential cross sections increase appreciably with the mean energy (or the temperature) $\langle\varepsilon_\nu\rangle$. This increase is depended also on the detector's excitation energy ω. In the case of the ^{64}Zn, our results show a pronounced response in the excitation region $\omega = 10 - 15$ MeV. This means that signals of supernova neutrinos of the type ν_x and $\tilde{\nu}_x$, $x = \mu, \tau$ (high mean energies), cause much stronger response in this range of excitations of the detector [8–10].

4 Summary and Conclusions

As can be seen, there is a rich response, not only in the particle-unbound energy region, but also in the particle bound energy region of the discrete spectrum. Obviously, the folded cross section is strongly dependent on the mean energy $\langle\varepsilon_\nu\rangle$. Also there is a clear temperature (T) increase of the folded cross section.

5 Acknowledgments

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References

[1] H. Ejiri, J. Engel, R. Hazama, P. Krastev, N. Kudomi, and R.G.H. Robertson, *Phys. Rev. Lett.* **85** (2000), 2917.

[2] K. Zuber, *Phys. Lett. B* **519** (2001), 1–7; *Prog. Part. Nucl. Phys.* **57** (2006), 235–240.

[3] V. Tsakstara, T.S. Kosmas, P.C. Divari, and J. Sinatkas, *AIP Conf. Proc.* **1180** (2009), 61.

[4] T.S. Kosmas and V. Tsakstara, *J. Phys. Conf. Ser.* **203** (2010), 012090.

[5] M.T. Keil, G.G. Raffelt, and H.T. Janka, *Astrophys. J.* **590** (2003), 971.

[6] N. Jachowicz and G.C. McLaughlin, *Phys. Rev. Lett.* **96** (2006), 172301.

[7] V. Tsakstara, T.S. Kosmas, V.C. Chasioti, and J. Sinatkas, *AIP Conf. Proc.* **972** (2008), 562.

[8] V. Tsakstara and T.S. Kosmas, *Prog. Part. Nucl. Phys.* **64** (2010), 407.

[9] V. Tsakstara, T.S. Kosmas, and J. Sinatkas, *Prog. Part. Nucl. Phys.* **66** (2011), 430-435.

[10] V. Tsakstara and T.S. Kosmas *Phys. Rev. C* (2011), in press.