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Review

Neutrino-nucleus reactions in terrestrial experiments and astrophysics

V. Tsakstara [a], T.S. Kosmas [a,b,*]

[a] *Theoretical Physics Section, University of Ioannina, GR 45110 Ioannina, Greece*

[b] *Institut für Theoretische Physik der Universität Tübingen, D-72076 Tübingen, Germany*

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ABSTRACT

We focus on the role and importance of neutrino-nucleus interactions to neutrino detection by terrestrial detector-nuclei and to various processes as well as scattering effects occurring inside the matter of stars (supernova, etc.) that generate the astrophysical neutrino energy spectra. We specifically concentrate on the parameterizations of the supernova neutrino energy distributions and examine the use of the low-energy β-beam spectra, originating from the boosted radioactive nuclei ^{6}He and ^{18}Ne, for such purposes.

1. Introduction

During recent decades the physics of neutrinos and the topics related to it has gained enormous momentum in astro-, nuclear and particle physics as well as in other areas such as cosmology and astronomy. However, many important questions such as the neutrino oscillations, neutrino properties, etc. remain to be answered. Nowadays, measurements of low-energy (MeV or tens of MeV) astrophysical neutrino fluxes, originating from the Sun, Earth, collapsing stars, etc., have become feasible. Moreover, there are expected significant advances in the theoretical understanding of the above neutrino production sources related to the role of neutrinos in the explosion mechanism of core collapse supernova and the role of the neutrino oscillations in this context [1,2].

Terrestrial neutrino experiments and telescopes provided crucial information about the weak processes taking place in the interior of stars thanks to the fact that neutrinos are extremely sensitive probes for studying stellar evolution and the astro-nuclear processes providing the main signal from distant stars. Thus, measurements of solar neutrinos (KAMLAND, Borexino, etc.) are 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 the solar core and clarify if the metallicity in the Sun is homogeneous.

On the other hand, recent stellar evolution models describing the explosion mechanism of type II supernovae have provided important information regarding the role of neutrinos in the evolution of massive stars, explosive nucleo-synthesis, etc. [3,4]. However, uncertainties on astrophysical interactions of neutrinos with matter are intimately related to our understanding of the neutrino-nucleus cross sections. In addition, neutrino experiments need good control over systematic errors coming from neutrino-nucleus cross section uncertainties at low and intermediate energies.

The present work focuses on the role and the significance of neutrino-nucleus interactions to the neutrino detection by terrestrial experiments as well as to their scattering inside the matter of stars (supernova, etc.) that determine the shape of the neutrino-energy spectra. We pay special attention to the parameterizations of the supernova neutrino energy spectra and the use of the low-energy β-beam spectra derived from the boosted radioactive nuclei ^{6}He and ^{18}Ne for their interpretation.

* Corresponding author.
E-mail address: hkosmas@uoi.gr (T.S. Kosmas).

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2. Supernova neutrino energy distributions

According to recent predictions of numerical simulations [3], the shape of the supernova neutrino energy distribution is determined by the conditions under which the neutrinos are emitted from the star. Intuitively, a thermal spectrum would correctly describe this energy distribution, but several interactions contribute in such a way that the spectral shape differs from a purely thermal one. Furthermore, the spectral shape is influenced by the fact that high-energy neutrinos leave the star promptly. These deviations could be considered by the introduction of a chemical potential parameter which makes the width of the spectrum narrow (pinching effect) as compared to the purely thermal shape.

A commonly employed distribution for supernova neutrino energy spectra is the Fermi–Dirac distribution described by the analytic expression

$$\eta_{FD}(\epsilon_\nu) = \frac{N_{FD}(\eta_{dg})}{T^3} \frac{\epsilon_\nu^2}{1 + \exp(\epsilon_\nu/T - \eta_{dg})}. \tag{1}$$

This is a convenient description for the energy distribution of supernova neutrinos [5–7] depending on the degeneracy parameter η_{dg} and on the temperature T of the burning shell from where neutrinos escape. In Eq. (1), $N_{FD}(\eta_{dg})$ is a normalization factor that depends on the degeneracy parameter η_{dg}. As it is supported by recent core collapse supernova simulations [3], the supernova-neutrino energy spectra can be rather accurately parameterized also by a power-law distribution of the form

$$\eta_{PL}(\epsilon_\nu) = N_{PL}(\alpha) \left(\frac{\epsilon_\nu}{\langle \epsilon_\nu \rangle} \right)^\alpha \exp\left(-\frac{(\alpha + 1)\epsilon_\nu}{\langle \epsilon_\nu \rangle} \right), \tag{2}$$

where $N_{PL}(\alpha)$ is a normalization factor depending on the pinching parameter α [5,7] and $\langle \epsilon_\nu \rangle$ denotes the average neutrino energy.

It is worth mentioning that the above neutrino energy distributions do not describe satisfactorily the high energy tail ($\epsilon_\nu \approx$ 60–100 MeV) of the supernova neutrino [7]. In this energy region other effects (such as the neutrino-neutrino interaction, neutrino oscillations, neutrino hierarchy problem, etc.) become important and must be also taken into account [1,7]. In the present work, however, we do not consider such effects since the nuclear excitations of interest lie in the energy region $E_x \leq$ 40–50 MeV.

Recently, the use of boosted β-decay radioactive nuclei was proposed as sources of neutrino-beams of low energy (β-beam neutrinos) [1,2,7,8]. The neutrino-beam obtained with this facility is intense, collimated and pure, i.e. appropriate for searching neutrino-nucleus interactions at low and intermediate energies and useful for the interpretation of supernova neutrino signals. Such studies are important for various open issues in nuclear, particle physics and astrophysics.

The energy distribution of the neutrinos coming out of the decaying boosted radioactive nucleus is obtained by considering the nuclear rest frame moving with velocity $u = \sqrt{\gamma^2 - 1}/\gamma$ with respect to the laboratory frame. Then, the laboratory frame energy distribution reads [9]

$$\eta_{\gamma_i}(\varepsilon_\nu) = \frac{ln2}{m_e^5 (ft)} \frac{F(\pm Z, E_e) E_e p_e \varepsilon_\nu^2}{\gamma^2 (1+u)^2 (2\gamma(1-u))}, \tag{3}$$

where m_e, E_e and p_e are the mass, energy and momentum, respectively, of the outgoing electron. (ft) is the known ft-value which involves the nuclear matrix element, and $F(\pm Z, E_e)$ is the Coulomb correction function, also known as Fermi function. This function accounts for the final state (Coulomb) interaction between the emitted electron (or positron) and the nuclear charge distribution. In the present work, for simplicity, we use the non-relativistic expression for the Fermi function $F(\pm Z, E_e)$ [10].

As has been addressed previously [2,6,8], by exploiting the spectra of low-energy β-beams one could construct a synthetic distribution $\eta_{fit}(\varepsilon_\nu)$ given by a linear combinations of boosted β-beam spectra η_{γ_i} as [8]

$$\eta_{fit}(\varepsilon_\nu) = \sum \alpha_{\gamma_i} \eta_{\gamma_i}(\varepsilon_\nu). \tag{4}$$

The exact expression of the synthetic spectrum $\eta_{fit}(\varepsilon_\nu)$ for use in the interpretation of supernova-neutrino results by minimizing, as proposed in Ref. [1,7], the expression

$$\int \mathrm{d}\varepsilon |\eta_{fit}(\varepsilon_\nu) - \eta_{SN}(\varepsilon_\nu)|, \tag{5}$$

which gives the best fit to the supernova-neutrino energy distribution $\eta_{SN}(\varepsilon_\nu)$. The minimization procedure employed in the present work is not very powerful like the one used in Ref. [5], however, it reveals the same main features that have been extensively discussed in Ref. [2].

In Fig. 1 we plot the normalized β-beam neutrino spectra generated from boosted radioactive ^{6}He nuclei (left), not discussed in detail previously, and ^{18}Ne nuclei (right), discussed in Ref. [5]. The boost factors γ used in Fig. 1 are integers between $\gamma = 3$ and $\gamma = 15$, as in Ref. [5].