Investigating the nuclear response of Te isotopes to SN-neutrinos

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Abstract. The response of Te isotopes to the energy-spectra of supernova neutrinos is explored by applying the folding procedure. We present double differential cross sections for \(^{128}\)Te and \(^{130}\)Te isotopes convoluted with a two-parameter Fermi-Dirac (FD) and a Power-Law (PL) neutrino energy distributions. The original cross sections are calculated in the context of the quasi particle random phase approximation (QRPA) by using realistic two-body forces.

1. Introduction

Recently, the detection of low-energy neutrinos is searched in conjunction with double beta and neutrinoless double beta decays by employing very-low threshold-energy detectors in terrestrial experiments [1, 2, 3, 4]. Among the various ongoing or planed double beta decay detectors, the Cd-based semiconductor detectors CdTe and CdZnTe, which are currently used to study various rare processes in several areas of physics (X-ray physics, astrophysics, medical applications, etc.), have been proposed to be used in the COBRA double beta decay experiment [4]. The great advantage of this experiment is related to the fact that the double beta emitters are part of the detectors themselves and, in contrast to scintillators, they have good energy resolution.

It is worth mentioning that the detector of this experiment (it has recently been funded) the stable Te isotopes participate by 40-45% and a systematic investigation of the response of these isotopes as low-energy neutrino detectors has not been addresses up to the present. We mention that CUORE experiment is using a TeO\(_2\) detector. It is the purpose of our present work to study the nuclear response to supernova neutrino energy spectra of all nuclear isotopes of COBRA detector. We, first, focus on the \(^{128,130}\)Te isotopes which have big abundances on the natural Te and about 40% in the matter of COBRA detector. To this aim, the cross sections obtained in the context of the QRPA are folded with a known neutrino-energy distribution (see Sect. 2) [2, 3]. The folding procedure could be subsequently carried out for integrated and total cross section as well [2, 3]. In this work, results of the convoluted double differential cross sections for neutral current reactions of neutrinos with \(^{128,130}\)Te isotopes are presented and discussed.

2. Supernova neutrino distributions

According to predictions of recent numerical simulations [1], the shape of the energy distributions of supernova neutrinos is determined by the conditions under which the neutrinos are emitted from the collapsing star. Even though the use of a thermal spectrum to describe the energy distribution of the supernova neutrinos is intuitively correct, various interactions cause deviations...
of the spectral shape from a purely thermal one. These deviations are described by the introduction of a chemical potential (degeneracy parameter \( \eta \)), narrowing the width \( w \) of the spectrum compared to the purely thermal shape, an effect referred to as pinching. Furthermore, the spectral shape is influenced by the fact that the neutrino cross section scales with the square of the lepton energy, forcing high-energy neutrinos to leave the star promptly.

In addition, the fact that different kinds of neutrinos are involved in different interactions, and that the reaction cross sections of the (anti-) neutrino depends on its energy, flavor, and helicity, modulates this picture. For all (anti-)neutrino flavors, the energies are in the range of a few to a few tens of MeV although calculations of neutrino transport that use different opacities achieve somewhat different spectra [1]. In the present work we employ the following distributions for supernova neutrino energy spectra.

2.1. The Fermi-Dirac distributions

Traditionally, Fermi-Dirac spectra described by the analytic expression

\[
\eta_{FD}(\epsilon_\nu) = \frac{N_{FD}(\eta)}{T^3} \frac{\epsilon_{\nu}^2}{1 + \exp(\epsilon_{\nu}/T - \eta)}
\]

where \( N_{FD}(\eta) \) is a normalization factor depending on the degeneracy parameter \( \eta \), were utilized as the convenient description for the energy distribution of supernova neutrinos [2, 3].

2.2. The power-law distributions

As it also supported by recent core collapse supernova simulations [1], the supernova-neutrino energy spectra can be rather accurately parameterized by a power-law distribution of the form

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

where \( N_{PL}(\alpha) \) is a normalization factor depending on the pinching parameter \( \alpha \) [2, 3].

It is worth mentioning that the above neutrino energy distributions are not very satisfactory in the high energy dail \( \epsilon_\nu \approx 60 - 80 \text{ MeV} \). In this energy region other important effects (like the neutrino-neutrino interaction, neutrino oscillations, neutrino hierarchy problem, etc.) must be taken into account [5, 6]. In the present work we do not consider such effects since the nuclear excitations derived by our QRPA method lie in the energy region \( E_x \leq 30 - 40 \text{ MeV} \) [7].

3. Results and discussion

In this work we studied folded double differential cross sections for \(^{128}\text{Te} \) and \(^{130}\text{Te} \) isotopes. By using the original results of the double differential cross sections obtained with our QRPA [7] and Eqs. (1) and (2) we calculated the corresponding folded cross sections as functions of the incoming neutrino energy \( \epsilon_\nu \) for a mean energy \( \langle E \rangle \) and various values of the width parameters \( w \) and temperature \( T \).

The results are illustrated in Fig. 1, for \(^{128}\text{Te} \) where a Fermi-Dirac distribution was used, and Fig. 2, for \(^{130}\text{Te} \) where a Power-law distribution was employed. More specifically, in Fig. 1 we plot the folded double differential cross section of \(^{128}\text{Te} \) for \( T = 2.57, 3.58 \text{ MeV} \) and \( \eta = 4.4, 1.1 \) while in Fig. 2, those of \(^{130}\text{Te} \) for pinching parameter values \( \alpha = 5.1, 2.7 \).

The plots of Figs. 1, and 2 have been obtained by varying the scattering angle from 0° to 180° with a step \( \Delta \Phi = 155° \). For a fixed value of the width \( w \) the peak of the folded cross section is shifted towards larger incoming neutrino energies \( \epsilon_\nu \) as the scattering angle \( \Phi \) increases.

The peaks lie around \( \epsilon_\nu = 20-30 \text{ MeV} \) for each fixed value of the scattering angle \( \Phi \). As can also be seen, there is a clear \( T \) and \( w \) dependent increase of the peak shown for each curve.

In conclusion, our results show a rich response of both isotopes to supernova neutrino spectra. A detailed study of the response of Te isotopes to SN neutrinos is done elsewhere [8].
Figure 1. Folded double differential cross sections for $^{128}$Te. A Fermi-Dirac (FD) distribution for width parameter values $w=0.7, 0.9$ and average neutrino energy $\langle E \rangle = 12$ MeV is used.

Figure 2. Same as in Fig. 1 but for $^{130}$Te with the use of a Power-Law (PL) distribution.

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