Neutral-current neutrino-nucleus reactions and their impact to supernova physics

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Abstract. We study neutral-current neutrino-nucleus reactions in nuclei that are relevant for supernova (SN) simulations and for terrestrial experiments aiming at neutrino astrophysics as well as ν-nucleus scattering cross sections measurements. Such studies allow us to improve estimates of nuclear responses to low energy neutrinos in light of the operation of nuclear ν-detectors with very-low threshold and very high sensitivity. The adopted ν-energy range is extended to rather high energies (up to 100 MeV) so as to consider allowed and forbidden multipole contributions to cross sections. Both contributions are calculated within the quasi-particle random phase approximation by using realistic two-body forces (Bonn CD potential) for the residual interaction of the nuclear Hamiltonian. As a special application the ⁵⁶Fe isotope is chosen due to its significant role in SN physics and ν-detection.

1. Introduction

Neutrinos are neutral particles (without electric charge and magnetic moment) having very small masses (according to the recent experimental evidences). Since they are not deflected from electromagnetic fields and interact very weakly gravitationally, they can travel cosmological large distances without interaction, so as they may escape the very dense surrounding deepest in the interior of massive stars [1]. This property makes them almost ideal messenger-particles of distant stars, a feature that allows us to look into the innermost part of the stars. However, the very low ν-interaction cross-section is simultaneously the biggest disadvantage for their detection that can be probed through measuring Cherenkov light from secondary particles or through the de-excitation products of ν-induced excitations of nuclear ν-detectors in extremely sensitive (mostly underground) experiments. Such probes, however, need significant event rates and, therefore, huge volume detectors have to be constructed [2, 3, 4]. On the other hand, from supernova (SN) physics it is known that, the death of massive (with mass \( M \geq 8 - 10M_\odot \)) stars is marked through very energetic explosions known as core-collapse supernovae. In a typical SN, an energy of about \( 10^{53} \) ergs is released (within 10 seconds after the explosion) in the form of neutrinos which (except their oscillation on propagation) travel to Earth undistorted.

In the present research plan, we explore the role of ν-nucleus reactions in understanding open questions relevant to SN physics. Our strategy is as follows: First, we consider neutral-current (NC) ν-nucleus scattering assuming that the nuclear target is at zero temperature, for some isotopes contents of promising ν-detection materials that are quite advantageous (Fe,
Ar, Mo, Te, etc.): (i) for measuring rare events (double-beta decay, etc. [5, 6]) and (ii) for potential use in studying neutrino physics issues [2, 3, 4]. Second, we treat charged-current (CC) interactions of neutrinos with the above nuclei. The relevant cross sections are by about an order of magnitude larger than the corresponding for NC ones. Third, we consider nuclear responses to SN-neutrinos focusing on the possibility of including in these estimations contributions coming from particle decays of $\nu$-induced excited states lying above the separation energies for protons and neutrons [4]. In studying detector responses to SN neutrinos, particle decays cause extra signals which are important to be included in the study.

As a concrete nuclear system in this paper, we examine the nucleus $^{56}$Fe, which plays a significant role in SN physics involving neutrinos. We note that, for the iron group isotopes in SN environment the important thermal effects on NC $\nu$-nucleus scattering have been studied [7, 8].

2. Neutrino-nucleus cross sections at zero temperature

By applying the Donnelly-Walecka multipole decomposition method [2], the double differential cross section of NC $\nu$-nucleus scattering reads

$$\frac{d^2\sigma_{\nu-A}}{dE d\Omega}(\phi, \theta, \omega, \varepsilon_i) = \delta(E_f - E_i - \omega) \frac{2G^2\varepsilon_f^2 \cos^2(\theta/2)}{\pi(2J_f + 1)} [C_V + C_A - C_{VA}] , \tag{1}$$

The $\delta$-function in the right hand side of the latter equation denotes the energy conservation, so as $\omega = \varepsilon_\nu - \varepsilon_f \approx E_f - E_i$, where $\omega$ is the excitation energy of the nucleus, $E_i$ and $E_f$ represent the energy of the initial (ground) and final states of the studied nucleus, respectively. $\varepsilon_\nu$ ($\varepsilon_f$) is the incoming (outgoing) neutrino energy.

The term $C_V$ ($C_A$) in Eq. (1) is a summation over the contributions coming from the polar-vector (axial-vector) operators written in terms of the matrix elements of the eight multipole operators $\hat{M}_f^{(5)}$, $\hat{T}_f^{(5)}$, $\hat{C}_{el}^{(5)}$ and $\hat{T}_f^{mag(5)}$, where the superscript '5' refers to the four axial-vector components of the hadronic current. The interference term $C_{VA}$ in Eq. (1) contains the product of transverse polar-vector and transverse axial-vector matrix elements [2] For normal parity transitions, $C_{VA}$ contains contributions of $\hat{T}_f^{el}$ and $\hat{T}_f^{mag(5)}$ operators while for abnormal parity ones $C_{VA}$ contains matrix elements of $\hat{T}_f^{mag(5)}$ and $\hat{T}_f^{el}$. Total cross sections, $\sigma$, are subsequently calculated by integrating (numerically) Eq. (1) as is described in Refs. [2, 3, 4].

2.1. Determination of the QRPA model parameters

The initial (ground) state ($|0^+\rangle$) of the even-even $^{56}$Fe isotope has been computed by solving the BCS equations. In Table 1, we tabulate the values of the pairing parameters ($g_{pair}^{p,n}$) and the energy gaps ($\Delta_{p,n}^{th}$) for protons ($p$) and neutrons ($n$) determined at the BCS level for this isotope. The first parameters renormalize the pairing force and adjust the gaps $\Delta_{p,n}^{th}$ to the empirical ones, $\Delta_{p,n}^{exp}$, obtained through the application of the well known three point formulae [4].

Table 1. Parameters $g_{pair}^{p,n}$, for protons ($p$) and neutrons ($n$), respectively, determining the BCS pairing interactions, and values of the energy gaps, $\Delta_{p,n}^{th}$. The latter are adjusted to reproduce the empirical energy gaps, $\Delta_{p,n}^{exp}$ for $^{56}$Fe ($b$ is the h.o. size parameter).

| Isotope  | $b$ (fm) | $g_{pair}^{p}$ | $g_{pair}^{n}$ | $S_p$ | $S_n$ | $\Delta_p^{exp}$ | $\Delta_n^{exp}$ | $\Delta_p^{th}$ | $\Delta_n^{th}$ |
|----------|---------|----------------|----------------|------|------|-----------------|-----------------|---------------|---------------|
| $^{56}$Fe | 1.996   | 0.901          | 0.849          | 10.184 | 11.197 | 1.568           | 1.568           | 1.366         | 1.363         |
The final (excited) states $|J^π_f⟩$ of the isotope in question have been calculated by solving the QRPA equations [2]. The model space used consists of the major shells with $N = 2, 3, 4 hω$ (inert core $^{16}$O) which include 14 single particle orbits. The excited states $|J^π_f⟩$ have been checked by comparing the low-lying QRPA spectrum with the corresponding experimental excitations by adjusting accordingly the parameters that renormalize the particle-particle ($g_{pp}$) and particle-hole ($g_{ph}$) channels of the residual two-body matrix elements entering the QRPA matrices [2].

3. Results and Discussion

In the present contribution, as a first step towards the above purposes, we apply the QRPA method to calculate NC $\nu$.\textsuperscript{56}Fe scattering cross sections focusing on the study of the behavior of the $\sigma(\omega, \varepsilon_\nu = const., T = 0)$ in various leading sets of multipole states (up to $J^\pi = 6^\pm$). The assumed incoming $\nu$-energy range is $0 \leq \varepsilon_\nu \leq 100$ MeV.

The results of such original state-by-state QRPA calculations for the most important multipolarities are illustrated in Fig. 1(a,b,c), for the positive parity transitions $0^+, 1^+$ and $2^+$, and in Fig. 1(d), for the negative parity transitions $1^-$. In this figure, the cross sections refer to $\varepsilon_\nu = 30$ MeV, but such plots could be also made for other values of $\varepsilon_\nu$. As it is, in general, expected, for inelastic scattering of SN neutrinos, the leading multipoles, which yield the most significant cross sections, are the $J^\pi = 1^+$ and $J^\pi = 1^-$. We have chosen to show $\sigma(\omega, \varepsilon_\nu = 30$ MeV), because $\varepsilon_\nu = 30$ MeV is rather close to the mean energies of SN $\nu_x$ neutrinos and $\bar{\nu}_x$ anti-neutrinos. Recent SN neutrino simulations suggest mean energies $\langle \varepsilon_{\nu_x} \rangle = \langle \varepsilon_{\bar{\nu}_x} \rangle = 22 - 25$ MeV [3].

As discussed in Ref. [2], the $1^-$ multipole contributions contain spurious admixtures which in the present work are approximately removed. The maximum peak appears in the case of the $1^+$ multipole, in which the axial-vector pieces $L_{1}^5$ and $T_{el_1}^{d5}$ dominate over the vector piece $T_{mag_1}^{mag}$. Since the momentum transfer $q$ is rather small for SN-neutrino scattering, the axial-vector

![Figure 1. NC $\nu$.\textsuperscript{56}Fe scattering cross sections $\sigma(\omega)$, as a function of the nuclear excitation energy $\omega$ for: $0^+$ (a), $1^+$ (b), $2^+$ (c) and $1^-$ (d) transitions ($\varepsilon_\nu = 30$ MeV).]
matrix elements dominate over the vector ones (even by an order of magnitude or more).

In Fig. 2, the variation of $\sigma(\omega, \varepsilon_{\nu} = \text{ct.})$ for the reaction $^{56}\text{Fe}(\nu, \nu')^{56}\text{Fe}^*$, is demonstrated. As can be seen, $\sigma(\omega)$ presents some characteristic clearly pronounced peaks at various excitation energies $\omega$ and specifically for transitions $J^\pi = 1^+ , 1^-$, but also for $J^\pi = 0^+, 2^+$. The maximum peak corresponds to a $J^\pi = 1^+$ (ground state) transition at $\omega = 9.482$ MeV and a second one corresponds to a $1^-$ transition at $\omega = 13.311$ MeV in agreement with the findings of Refs. [2, 4].

4. Summary and Conclusions
Neutral-current $\nu$-nucleus reactions cross sections in nuclei that are important for SN simulations and for terrestrial experiments aiming at astrophysical $\nu$-detection, are required. A great number of open issues in supernova physics may be unraveled by future galactic (or extragalactic) SN explosions which nowadays may well be analyzed with very high statistics by Earth experiments.

In this work, we focused on cross section calculations of the reaction $^{56}\text{Fe}(\nu, \nu')^{56}\text{Fe}^*$ (at zero temperature). At finite temperature in stellar environment, thermal population of the excited states may enhance the weak interaction rates and cross sections at low $\nu$-energies. Thermal effects for NC $\nu$-scattering on Fe group isotopes are important to understand SN dynamics as discussed in Refs. [8, 9, 10].

References
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Figure 2. Cross section $\sigma(\omega)$ as a function of the excitation energy $\omega$ for the nucleus $^{56}\text{Fe}$. The incoming $\nu$-energy was $\varepsilon_{\nu} = 40$ MeV. The most pronounced peaks belong to $J = 1$ transitions.