PROCEEDINGS OF SCIENCE

Neutral-Current Neutrino-Nucleus Inelastic Reactions for Core Collapse Supernovae

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We study neutrino-nucleus inelastic reactions of pf-shell nuclei for core-collapse supernovae. Cross-sections are computed taking into account detailed nuclear response and thermal excitation of nuclear states.

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[†] A footnote may follow.

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1. Introduction

Neutrino reactions are important in many astrophysical scenarios. In supernova they play a fundamental role in the dynamics of the collapse and evolution of the post-bounce shock as well as in the following explosive nucleosynthesis. During the collapse phase, neutrinos are produced mainly in electron captures and they escape the star's core carrying energy away. About 99% of the energy available from gravitational collapse is lost in the form of neutrinos. However, with densities in excess of $\rho \sim 10^{11}$ g cm^{-3}, neutrino interactions with matter become important in the time-scale of the collapse and, eventually, equilibrium between neutrinos and matter is established - neutrino thermalization takes place ($\rho \approx 10^{12}$ g cm^{-3}). To date, collapse simulations have considered neutrino inelastic scattering on electrons and free nucleons as the main mechanism for thermalization. However, in 1988, Haxton argued that the excitation of the nuclear giant resonances in the supernova environment can lead to significant cross-sections of inelastic neutrino-nucleus reactions and these should, therefore, be added in supernova simulations [1]. Moreover, recently improved nuclear models have shown that electron capture rates on nuclei dominate captures on free protons and suggested the same might be the case for neutrino-nucleus reactions [2, 3].

The pioneering study of inelastic neutrino scattering and absorption reactions on nuclei in supernova was done by Bruenn and Haxton [4]. In their study, the nuclear composition was approximated by a single nucleus - ^{56}Fe - and the rates were calculated based on a nuclear model appropriate for temperatures $T = 0$. They found that inelastic neutrino-nucleus scattering plays an important role in equilibrating neutrinos with matter. More recently, noticeable finite-temperature effects in the low-energy cross-sections were found by Sampaio *et al.*, using results from large-scale Shell-Model calculations of the allowed GT transitions [5, 6]. The study was performed on representative nuclei, suggesting nuclear structure effects on the finite-temperature dependence of the cross-sections.

Following up this work, neutral-current neutrino-nucleus inelastic reactions were studied on a larger set of *iron group* nuclei relevant in the supernova composition[10]. The cross-sections were extended to higher neutrino energies and forbidden transitions were added. Here, we recall the main results of this study, but also new results of folded cross-sections over the nuclear composition are shown for relevant stellar conditions.

2. Model

To describe the neutral-current neutrino-nucleus inelastic reaction, we split the cross-section into two components:

$$\sigma_\nu = \sigma_\nu^{\mathrm{SM}} + \sigma_\nu^{\mathrm{RPA}} \tag{2.1}$$

where σ_ν^{SM} describes the (allowed) neutral Gamow-Teller, GT_0, contributions, derived from large-scale Shell-Model (SM) diagonalization of pf-shell nuclei [7]; and $\sigma_\nu^{\mathrm{RPA}}$ describes the higher multipole (forbidden) transitions, derived from the Random Phase Approximation (RPA) [8]. The SM component accounts for detailed nuclear structure, correlations and finite-temperature effects, which are important for low-energy neutrino scattering ($E_\nu^i \leq 15$ MeV). To derive it, we use the same procedure as in [5, 6]: The SM component is split into one term describing neutrino

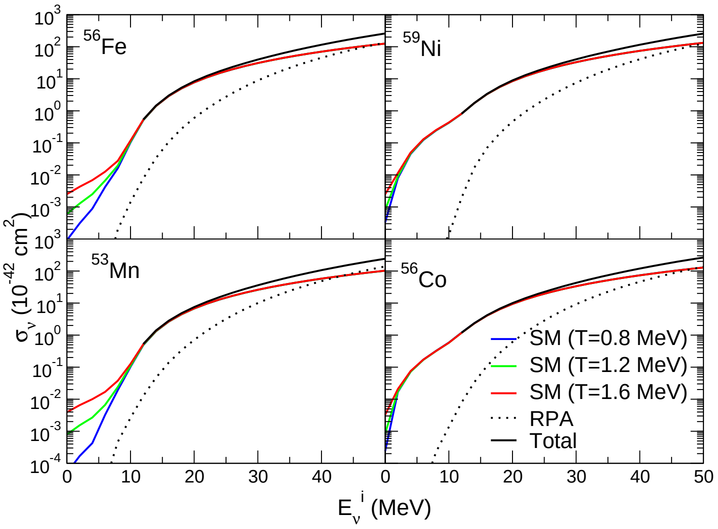

Figure 1: Neutral-current inelastic neutrino-nucleus cross-sections for four selected nuclei and three finite-temperatures.

down-scattering ($E_\nu^f < E_\nu^i$), independent of temperature, and another term describing neutrino up-scattering ($E_\nu^f > E_\nu^i$), which depends on temperature. At high neutrino energies, scattering is dominated by the bulk properties (total strength and centroid) of the higher multipole resonances, which can be well described by the RPA. Our RPA calculations were done within the Independent Particle Model occupation number formalism and, hence, this component is independent of temperature.

3. Results and discussion

Finite-temperature effects of low energy neutrino-nucleus cross-sections are strongly dependent on the energy of the centroid of the GT_0 giant resonances ($E_x \approx 10$ MeV) and on the density and relative transition strengths of the low-lying states. Cross-sections for four selected nuclei as a function of the initial neutrino energy are shown in Fig. 1 for three different temperatures: $T = 0.8$ MeV ($\sim 0.9 \times 10^{10}$ K), $T = 1.2$ MeV ($\sim 1.4 \times 10^{10}$ K) and $T = 1.6$ MeV ($\sim 1.9 \times 10^{10}$ K). These temperatures roughly correspond to the presupernova, neutrino trapping and neutrino thermalization phases of the core-collapse supernova evolution. Enhancement due to thermal excitation is notable for $E_\nu^i \leq 10$ MeV, especially in even-even nuclei (^{56}Fe) and some odd-A nuclei with a closed $f_{7/2}$ neutron orbit (^{53}Mn). These effects become negligible once E_ν^i is large enough to allow for transitions to the GT_0 centroid. For $E_\nu^i \sim 30-50$ MeV allowed and forbidden transitions contribute about equally to the cross-section, while at $E_\nu^i > 100$ MeV, forbidden transitions dominate [10].

A new process that is possible when one considers thermal excitations is neutrino up-scattering ($E_\nu^f > E_\nu^i$). This effect is best shown by final state neutrino energy distributions. Fig. 2 shows the

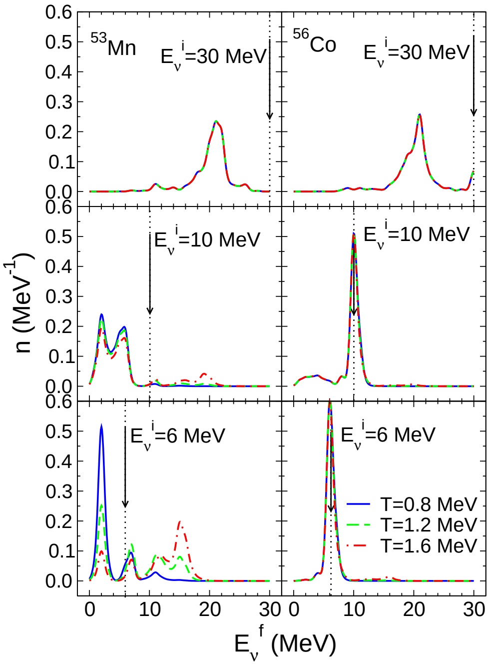

Figure 2: Normalized final state neutrino spectra for two nuclei and three initial neutrino energies and three temperatures.

normalized final state neutrino spectra for two nuclei and for three initial neutrino energies. Up-scattering is notable for $E_\nu^i = 6$ MeV in ^{53}Mn. Like in ^{56}Fe these excitations are important for nuclei with a small density of low-lying GT_0 states. Thermal excitations are less important when neutrinos are down-scattered by low-lying states, mailly in odd-A and odd-odd nuclei, here represented by ^{56}Co and ^{59}Ni. At $E_\nu^i = 30$ MeV neutrinos are essentially down-scattered by the bulk of the GT resonances for all nuclei.

Supernova simulations require cross-sections folded over the stellar nuclear composition, defined as:

$$\langle \sigma_\nu \rangle = \frac{\sum_k Y_k \sigma_\nu^k}{\sum_k Y_k} \tag{3.1}$$

where Y_k is the number abundance of the nucleus k for a given density (ρ), electron fraction (Y_e) and temperature (T). Here we use abundances given by the NSE Equation of State [9].

Fig. 3 illustrates the folded cross-sections over a pool of 52 *iron group* nuclei for three temperatures and three densities (ρY_e). Thermal enhancement of $E_\nu^i < 5$ MeV cross-sections is notable over the nuclear pool. Above $E_\nu \approx 15$ MeV, cross-sections can be parameterized by scattering from an *average nucleus*, chosen to approximate the matter composition.

Folding of neutral-current neutrino-nucleus inelastic cross-sections was done for a large number of stellar conditions and the results of the impact in supernova simulations are expected soon.

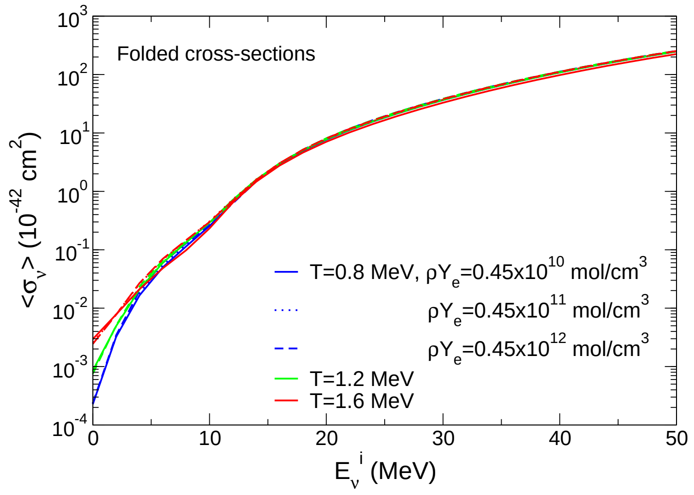

Figure 3: NSE-folded cross-sections over a pool of 52 pf-shell nuclei for three temperatures and three densities. Density-dependence is negligible compared with temperature-dependence of the cross-sections.

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