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Neutrino-nucleus reactions and their role in supernova dynamics and nucleosynthesis

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Abstract. Neutrino reactions on nuclei play important roles for the dynamics of supernovae and their associated nucleosynthesis. This manuscript summarizes the current status in deriving the relevant cross sections for supernova neutrinos and briefly discusses a few recent advances in supernova simulations where these reactions play a role.

1. Introduction

Neutrinos are key-players for the supernova dynamics [1, 2]. During the collapse phase the main neutrino source is electron capture on nuclei [3, 4]. By lowering the electron-to-nucleon ratio Y_e this process reduces the pressure which electrons can stem against the gravitational collapse of the core. Furthermore, at sufficiently low densities the electron neutrinos generated by the capture process can leave the star unhindered keeping the core at relatively low entropies so that heavy nuclei survive the collapse. At densities in excess of about 10^{12} g/cm^3 neutrinos get trapped in the core, mainly by elastic scattering on nuclei. The thermalization of neutrinos with the other core matter occurs by energy exchange via inelastic scattering on electrons and, in a lesser extent, on nuclei. In the final collapse phase at high densities pair production of neutrinos of all flavors becomes relevant. This occurs mainly by nucleon-nucleon bremsstrahlung [5, 6], but also nuclear deexcitation has been identified recently as an important additional source of neutrinos other than electron neutrinos [7]. After core bounce, energy transport by neutrinos from hotter core regions to the matter behind the stalled shock helps to revive the shock [8, 2]. The dominating processes are absorption of electron neutrinos and anti-neutrinos on neutrons and protons. The competition of these two absorption processes also determines the proton-to-neutron ratio for the subsequent explosive nucleosynthesis which might occur either in proton-rich environment (νp process [9, 10, 11]) or in neutron-rich environment. The later scenario has been favored for many years as the possible site for the astrophysical r-process (neutrino-driven wind model, [12]), but recent supernova simulations indicate that the conditions in the neutrino-driven wind are probably only sufficient to support a weak r-process which contributes to the observed r-process abundances up to the barium mass region (second r-process peak, e.g. [13]). There have been several suggestions how neutrino reactions on nuclei might contribute to supernova r-process nucleosynthesis (e.g. [14, 15, 16]), but recent studies point to no significant influence of these processes. Neutrino-induced spallation reactions, however, are crucial, for the production of selected nuclei (ν process [17]). Finally, the observation of supernova neutrinos by earthbound detectors is an emminent tool to verify our understanding of the supernova dynamics and mechanism. One requisite here is the knowledge of the neutrino reaction cross sections for the nuclei comprising the detector material.

There has been a recent extensive review of neutrino-nucleus reactions and their role in supernovae which might be consulted for more details [18].

2. Cross section models

Supernova neutrinos of interest here have relatively low energies (up to a few 10's of MeV). At these energies the cross sections are dominated by allowed transitions. Forbidden transitions become relevant at the higher neutrino energies and in cases where allowed transitions are strongly suppressed [19]. The Fermi contribution to the cross sections are defined by the position of the Isobaric Analog State and the respective sum rule. Charge-exchange experiments have progressed our understanding of Gamow-Teller (GT) distributions significantly in the last two decades [20]. The distributions are strongly fragmented. This is caused by nucleon-nucleon correlations and is well described by nuclear models like the diagonalization shell model which accounts for such correlations [21, 4, 22]. In fact, the combined progress due to experimental GT data from charge-exchange experiments and their detailed description by shell model calculations (except for a constant renormalization factor) have led to a rather reliable description of stellar electron capture [23, 24, 25, 26] which is the dominating weak interaction process during the collapse phase [3, 2]. The absorption of neutrinos on nuclei is the inverse process of electron and positron capture. Its calculation has also benefitted from the advances in describing GT distributions. In supernova simulations it is incorporated via detailed balance with the inverse capture processes. Forbidden transitions become relevant at neutrino energies high enough that reliable cross section calculations only require the reproduction of the energy centroids and total strengths of the respective transitions distributions, but not their detailed description. These requirements are fulfilled by the Random Phase Approximation (RPA). Hence a 'hybrid model' has been proposed in which the allowed contributions to the neutrino-nucleus cross sections are calculated by the shell model and the forbidden contributions within the RPA formalism [27].

Inelastic neutrino-nucleus scattering can be also evaluated within the hybrid model ansatz for temperature $T = 0$. Validation for this procedure can be derived from precision M1 data for spherical nuclei, measured by inelastic electron scattering, which are dominated by the same nuclear transitions [28]. At stellar temperatures, however, transitions mediated from thermally populated excited nuclear states modify the cross sections at low neutrino energies significantly. Two approaches have been proposed to incorporate these modifications: i) by including selected GT transitions involving excited states [28] and ii) within the consistent extension of the RPA to finite temperatures (Thermal Quasiparticle RPA) [29, 30].

Neutrino-nucleus reactions often excite the daughter nucleus to states above particle thresholds which then subsequently decay by particle emissions. The probabilities for decay into different particle channels can be calculate within the statistical model. Nuclear spallation reactions are important for supernova nucleosynthesis and potentially also as detection signal for certain supernova neutrino detectors.

3. Neutrino-nucleus reactions in supernova dynamic and nucleosynthesis

In this section we briefly summarize selected recent examples in which the role of neutrino-nucleus reactions have been investigated for the dynamics of core-collapse supernovae, for the production of selected nuclei in the ν nucleosynthesis process and for the spectrum of supernovae neutrinos and their observation by earthbound detectors.

3.1. Nuclear deexcitation by neutrino pair production

Meyer and Fuller have proposed that the deexcitation of thermally populated states by neutrino-pair production might be an important cooling mechanism of the supernova core during the collapse phase [31]. Recently this process has been incorporated for the first time into a supernova simulation and its role studied [7]. The relevant cross sections have been derived within two different models: i) on the basis of the independent particle model [31] and ii) by parametrization of the allowed and forbidden transition strengths guided by experiment or model calculations [7]. Although these cross section descriptions are both quite simplistic, they are reasonable enough to draw several important conclusions from the supernova simulation. The most important result is that nuclear deexcitation by neutrino-pair production does not influence the supernova dynamics. This is confirmed in Fig. 1 which shows that the luminosities of electron neutrinos, arising mainly from electron capture, are about 4 orders of magnitude larger than those of heavy-flavor neutrinos during the collapse phase. After bounce, nuclei are dissociated into free nucleons and neutrino-pair nuclear deexcitation becomes irrelevant. However, the simulation implies that this process is the main source of μ and τ neutrinos and of $\bar{\nu}_e$ during collapse. This is demonstrated in Fig. 1. At high densities of order 10^{13} g/cm^3 also nucleon-nucleon bremsstrahlung becomes a significant source of neutrinos other than ν_e which causes the steep rise of the $\nu_{\mu,\tau}$ and $\bar{\nu}_e$ luminosities at times just before bounce.

3.2. Neutrino nucleosynthesis

When neutrinos, produced in the hot supernova core, pass through the outer shells of the star, they can induce nuclear reactions and in this way contribute to the elementsynthesis (the ν-process, [17]). For example, the nuclides ^{11}B and ^{19}F are produced by $(\nu, \nu' n)$ and $(\nu, \nu' p)$ reactions on the quite abundant nuclei ^{12}C and ^{20}Ne. These reactions are dominantly induced by ν_μ and ν_τ neutrinos and their antiparticles (combined called ν_x neutrinos) which have larger average energies than ν_e and $\bar{\nu}_e$ neutrinos. As found in detailed stellar evolution studies [32] the rare odd-odd nuclides ^{138}La and ^{180}Ta are mainly made by the charged-current reaction ^{138}Ba$(\nu_e, e^-)^{138}$La and ^{180}Hf$(\nu_e, e^-)^{180}$Ta. Hence, the ν-process is potentially sensitive to the spectra and luminosity of ν_e and ν_x neutrinos, which are the neutrino types not observed from SN1987a.

Recent supernova simulations, with improved descriptions of neutrino matter interactions, indicate that the average neutrino energies are smaller than previously assumed [33]. This should result in reduced neutrino-induced cross sections and hence lower elemental production rates. This has been the motivation of recent neutrino nucleosynthesis studies performed for stars with masses between 15 and 40 $M_\odot$ and including neutrino-nucleus cross sections for a large set of nuclei with $Z < 78$. As an additional improvement in comparison to previous calculations these nucleosynthesis studies considered differential cross sections for multi-particle emissions [34]. Mainly due to the change in neutrino spectra, this study finds slightly smaller abundances for ^{7}Li, ^{11}B, ^{138}La and ^{180}Ta, however, it confirms the production of these nuclides by neutrino nucleosynthesis [33]. The study also finds that neutrino-induced reactions, either directly or indirectly by providing an enhanced abundance of light particles, noticeably contribute to the production of the radioactive nuclides ^{22}Na and ^{26}Al, which are both prime candidates for gamma-ray astronomy. However, the studies do not find significant production of two other candidates, ^{44}Ti and ^{60}Fe, due to neutrino-induced reactions.

As a major improvement it has been possible recently to measure the GT strengths on ^{138}Ba and ^{180}Hf below the particle thresholds and to convert these data into the relevant (ν_e, e^-) cross sections [35]. It is found that the new cross sections are slightly larger than the RPA predictions.

Due to the expected hierarchy of average energies for supernova neutrinos ($\langle E_{\nu_e} \rangle < \langle E_{\nu_x} \rangle$, neutrino oscillations are expected to increase the average ν_e energy and consequently also the charged-current cross section induced by supernova neutrinos. As pointed out by Kajino and collaborators, this makes the ratio of ^{7}Li and ^{11}B sensitive to the θ_{13} mixing angle and to the mass hierarchy [36, 37, 38]. Despite this intriguing sensitivity, an accurate derivation of the ^{7}Li/^{11}B abundance ratio requires reliable stellar model calculations and neutrino and nuclear

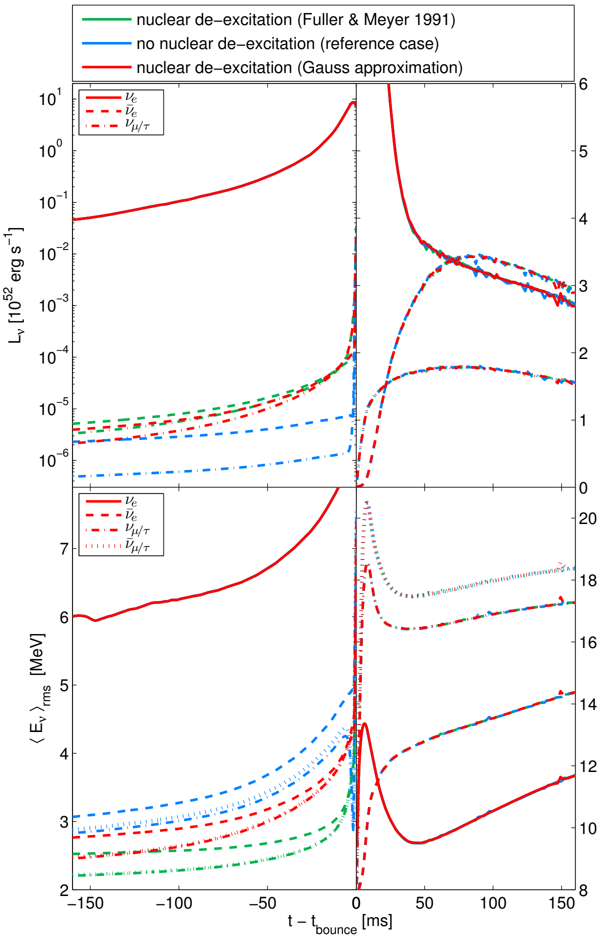

Figure 1. Evolution of neutrino luminosities and average energies from a core-collapse supernova simulation of an 11.2 $M_\odot$ progenitor star including the production of neutrino pairs from heavy-nuclei de-excitations, based on Ref. [31] (green lines) and the Gauss ansatz (see text, red lines), in comparison to a simulation that uses identical input physics, but neglects the nuclear deexcitation process (blue lines). (from [7]).

cross sections, but must also consider the production of the elements from other astrophysical sources; ^{7}Li is, for example, also produced by Big Bang nucleosynthesis [39].

3.3. Detecting supernova neutrinos

The observation of neutrinos from supernova SN1987A by the earthbound detectors Kamiokande [40] and IMB [41] has confirmed and advanced the understanding of core-collapse supernovae. A similar boost is expected from the observation of the next near-by supernova which is likely to test the predictions of supernova models concerning the neutrino spectra for the different flavors, including the noticeable neutrinoburst signal in electron neutrinos [2], originating from electron capture on protons set free by the shock. The prediction for this spectrum has changed recently after inelastic neutrino-nucleus scattering has been included in supernova simulations [42]. These burst neutrinos traverse regions outside the shock where nuclei have yet not been dissociated and, in particular, high-energy neutrinos excite these nuclei. This means that they are down-scattered in energy, in this way significantly reducing the high-

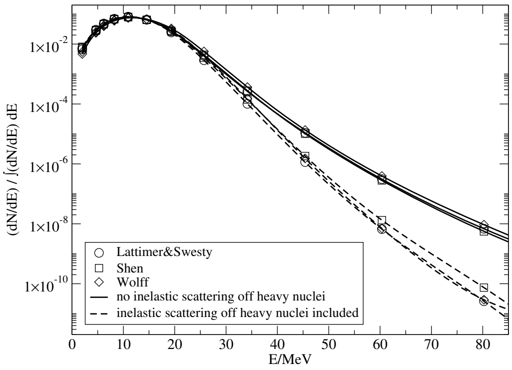

Figure 2. Normalized ν_e number spectra radiated during the shock breakout burst as seen by a distant observer at rest. Results are shown for simulations with three different nuclear EoSs. For better comparison of the strongly time-dependent spectra during this evolution phase, integration in a window of 8 ms around the peak luminosity was performed. Inelastic neutrino scattering off nuclei (dashed lines) leads mostly to energy losses of high-energy neutrinos and thus reduces the high-energy tails of the spectra. The vertical line marks the mean spectral energy. (from [42])

energy tail of the spectrum of emitted supernova neutrinos (see Fig. 2, [42]). This makes the detection of neutrinos, originating from the burst, by earthbound detectors more difficult, as the neutrino detection cross section scales with E_ν^2. Depending on the neutrino reaction threshold the reduction of the expected event rate can be significant, reaching up to more than 50% for ^{16}O which has been proposed, via nucleon emission following neutral current excitation, as a potential detection scheme for supernova ν_x neutrinos in Superkamiokande [43].

For a recent overview on the detectors and their scheme for observing supernova neutrinos the reader is refered to Ref. [44]. Table 2 of this reference lists the present and future supernova neutrino detectors. Their main material are liquid scintillator ($\mathrm{C}_n\mathrm{H}_{2n}$), water, lead or liquid argon. Hence translating the event rates of supernova neutrinos observed in the detectors requires a detailed knowledge of the cross sections for the neutrino interaction with the detector materials.

For ^{12}C shell model calculations have been performed for charged- and neutral-current neutrino reactions in a (0+2)$\hbar\omega$ model space [45], improving earlier calculations based on the RPA or on more restricted shell model spaces (see [19]). For the double-magic nucleus ^{16}O GT transitions are strongly suppressed and the cross sections are dominated by spin-dipole transitions which have recently been modelled in a shell model calculation [46] considering the *p* and *sd* shells. Based on a hybrid model approach calculating the GT contribution within the shell model, the transition to the IAS from the Fermi sum rule and the forbidden transitions within the RPA, Suzuki and Honma have determined the $^{40}\mathrm{Ar}(\nu_e, e^-)^{40}\mathrm{K}$ cross section for neutrino energies up to $E_\nu = 100$ MeV [47]. A similar study of the $(\bar{\nu_e}, e^+)$ cross section on ^{40}Ar has yet not been performed. As the GT contribution to the cross section is strongly suppressed such a study likely requires a shell model calculation performed in the (sd)-(pf) model space for the forbidden transitions. For ^{208}Pb Suzuki and Sagawa presented (ν_e, e^-) cross sections which have been obtained using GT data from a (p, n) experiment and adjusting their Hartree-Fock + Tamm-Dancoff approach for the first-forbidden response to the peaks of the spin-dipole resonances [48]. Furthermore, the spreading and quenching of the GT response has been considered by coupling to 2p-2h configurations. However, the calculations have been performed assuming a muon-decay-at-rest rather than a supernova neutrino spectrum, and are thus not directly relevant to supernova neutrinos.

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