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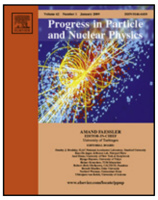

Review

# Neutrino–nucleus reaction in supernovae

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ABSTRACT

Neutrino reactions play an important role at various stages of core-collapse supernova. During infall, neutrinos are produced by electron capture mainly on nuclei and contribute significantly to the cooling of the collapsing core. After core bounce the nascent neutron star cools by neutrino emission. It is a major goal to observe such neutrinos from a future supernova by earthbound detectors and to establish their spectra. Recently it has been shown that the spectrum of electron neutrinos from the early neutrino burst is significantly altered if inelastic neutrino–nucleus scattering is considered in supernova simulations. Finally spallation reactions induced by neutrinos when passing through the outer burning shells can produce certain nuclides in what is called neutrino nucleosynthesis.

## 1. Some introductory remarks

Massive stars end their lives as type II supernovae, triggered by a collapse of their central iron core with a mass of more than 1 $M_\odot$ [1]. Despite improved description of the microphysics entering the simulations and sophisticated neutrino transport treatment spherically symmetric simulations of core-collapse supernovae fail to explode [2–4]; i.e. the energy transported to the stalled shock, which triggers the explosion, by absorption of neutrinos on free neutrons and protons is not sufficient to revive the shock wave which has run out of energy by dissociating the matter it traverses into free nucleons. However, the revival is successful in two-dimensional simulations as convection supported by hydrodynamical instabilities increases the efficiency by which neutrinos carry energy to the shock region. Successful two-dimensional simulations are reported in [5–7].

In the following we discuss specific recent improvements which enter the supernova simulations.

## 2. Electron capture in core-collapse supernovae

During most of the collapse the equation of state is given by that of a degenerate relativistic electron gas [1]; i.e. the pressure against the gravitational contraction arises from the degeneracy of the electrons in the stellar core. However, the electron chemical potential at core densities in excess of $10^8$ g/cm$^3$ is of order MeV and higher, thus making electron captures on nuclei energetically favorable. As these electron captures occur at rather small momentum transfer, the process is dominated by Gamow–Teller transitions; i.e. by the GT$_+$ transitions, in which a proton is changed into a neutron.

When the electron chemical potential $\mu_e$ (which grows with density as $\rho^{1/3}$) is of the same order as the nuclear $Q$ value, the electron capture rates are very sensitive to phase space and require a description of the detailed GT$_+$ distribution of the nuclei involved which is as accurate as possible. Furthermore, the finite temperature in the star requires the implicit

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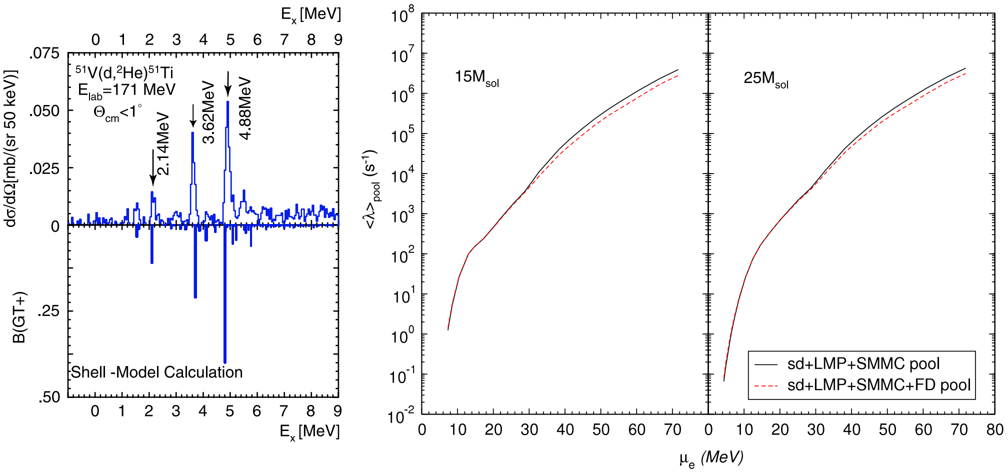

**Fig. 1.** Left: Comparison of the measured $^{51}$V($d$, $^2$He)$^{51}$Ti cross section at forward angles (which is proportional to the GT$_+$ strength) with the shell model GT distribution in $^{51}$V (from [21]). Right: Comparison of NSE-averaged electron capture rates calculated for about 3000 individual nuclei (solid, see text) with those obtained for the restricted set of nuclei (dashed) considered in [15] (from [16]).

consideration of capture on excited nuclear states, for which the GT$_+$ distribution can be different than for the ground state. It has been demonstrated [8,9] that modern shell model calculations are capable to describe GT$_+$ distributions rather well [10] (an example is shown in Fig. 1) and are therefore the appropriate tool to calculate the weak-interaction rates for those nuclei ($A \sim 50$–65) which are relevant at such densities [11]. At higher densities, when $\mu_e$ is sufficiently larger than the respective nuclear $Q$ values, the capture rate becomes less sensitive to the detailed GT$_+$ distribution and depends practically only on the total GT strength. Thus, less sophisticated nuclear models might be sufficient. However, one is facing a nuclear structure problem which has been overcome only very recently. Once the matter has become sufficiently neutron-rich, nuclei with proton numbers $Z < 40$ and neutron numbers $N > 40$ will be quite abundant in the core. For such nuclei, Gamow–Teller transitions would be Pauli forbidden [12] (GT$_+$ transitions change a proton into a neutron in the same harmonic oscillator shell) were it not for nuclear correlation and finite temperature effects which move nucleons from the *pf* shell into the *gds* shell. To describe such effects in an appropriately large model space (e.g. the complete *fpgds* shell) is currently only possible by means of the Shell Model Monte Carlo approach (SMMC) [13,14]. In [15] SMMC-based electron capture rates have been calculated for the more than 100 nuclei. Together with the shell model results for *fd* shell nuclei [9] a compilation of electron rates is available which covers the composition during the early collapse phase well (until densities to a few $10^{10}$ g/cm$^3$). However, at even higher densities the continuous electron capture drives the matter composition to more neutron-rich and heavier nuclei than considered in [15]. The neglect of these nuclei could lead to a systematic overestimate of the capture rates as the neglected nuclei have larger $Q$ values and enhanced Pauli blocking due to increased neutron excess than the nuclei considered. Unfortunately an SMMC evaluation of the several thousands of nuclei present in the matter composition during the late phase of collapse before neutrino trapping is numerically not feasible. Hence a simpler approach has to be adopted. This is based on the observation that the single particle occupation numbers obtained in the SMMC calculations can be well approximated by a parametrized Fermi–Dirac distribution. By adjusting the parameters of this distribution to the SMMC results for about 250 nuclei, occupation numbers were derived for nearly 3000 nuclei and the respective individual rates have been calculated within an RPA calculation based on these partial occupations. It is found that this simplified approach reproduces the SMMC results quite well at electron chemical potential $\mu_e > 15$ MeV [16]. This corresponds to the density regime where the previously neglected nuclei become abundant in the matter composition. At smaller electron chemical potentials (i.e. at lower densities) details of the GT distribution are important which are not recovered by the simple parametrized approach. However, at these conditions electron capture is dominated by nuclei for which individual shell model rates exist.

Fig. 1 compares the capture rate derived for the pool of more than 3000 nuclei (i.e. combining the rates from shell model diagonalization, SMMC, and from the parametrized approach) with those obtained purely on the basis of the shell model results. While the agreement is excellent at small electron chemical potentials (here the shell model rates dominate), the rates for the large pool are slightly smaller at higher $\mu_e$ values due the presence of neutron-rich heavy nuclei with smaller individual rates. Furthermore the new rates also include plasma screening effects which lead to an increase of the effective $Q$ values and a reduction of the electron chemical potential, which both reduce the electron capture rates. However, the effect is rather mild and does not alter the conclusion that electron capture on nuclei dominates over capture on protons during the collapse.

The shell model capture rates have significant impact on collapse simulations. In the presupernova phase ($\rho < 10^{10}$ g/cm$^3$) the captures proceed slower than assumed before and for a short period during silicon burning $\beta$-decays can compete [17,18]. As a consequence, the core is cooler, more massive and less neutron-rich before the final collapse. However, until recently simulations of this final collapse assumed that electron captures on nuclei are prohibited by the Pauli