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Review

Nuclear quests for supernova dynamics and nucleosynthesis

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ABSTRACT

Nuclear physics plays a crucial role in various aspects of core-collapse supernovae. The collapse dynamics is strongly influenced by electron captures. Using the modern many-body theory, improved capture rates have been derived recently with the important result that the process is dominated by capture on nuclei until neutrino trapping is achieved. Following the core bounce the ejected matter is the site of interesting nucleosynthesis. The early ejecta are proton-rich and give rise to the recently discovered νp-process. Later ejecta might be neutron-rich and can be one site of the r-process. The manuscript discusses recent progress in describing nuclear input relevant for the supernova dynamics and nucleosynthesis.

1. Introduction

Massive stars end their lives as core-collapse supernovae, triggered by a collapse of their central iron core with a mass of more than $1M_\odot$ [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] (however, see [5] who consider a quark-hadron phase transition at relatively low densities); 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 [6–8].

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 μ_e (which grows with density like $\rho^{1/3}$) 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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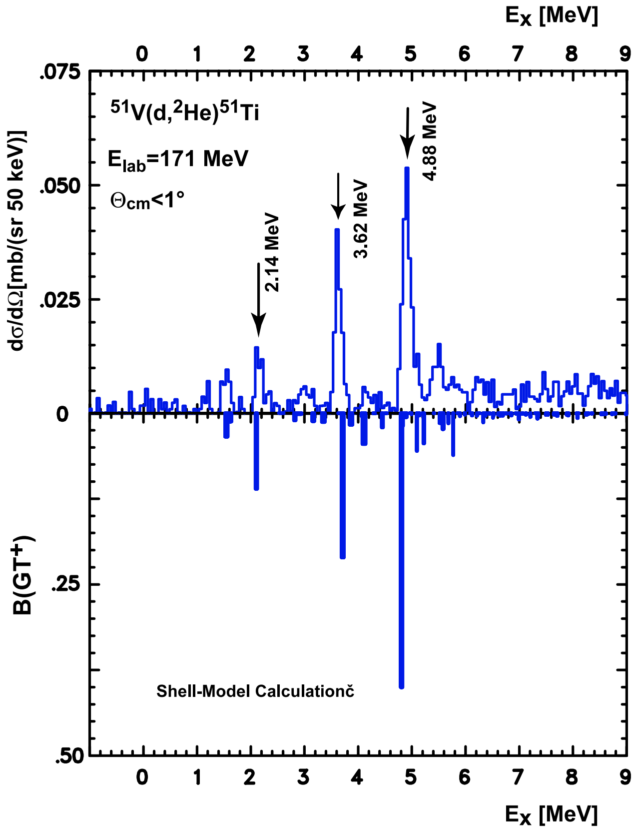

Fig. 1. Comparison of the measured ^{51}V(d, ^{2}He) ^{51}Ti cross section at forward angles (which is proportional to the GT_+ strength) with the shell model GT distribution in ^{51}V.
Source: From [17].

consideration of capture on excited nuclear states, for which the GT_+ distribution can be different from that for the ground state. It has been demonstrated [9,10] that modern shell model calculations are capable to describe GT_+ distributions rather well [11] (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 [12]. At higher densities, when μ_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 [13] (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) [14,15]. In [16] SMMC-based electron capture rates have been calculated for more than 100 nuclei.

Recently the GT_+ strength for ^{76}Se (with $Z = 34$ and $N = 42$) has been measured [18]. Indeed it is experimentally observed that cross-shell correlations induce a non-vanishing GT_+ strength which is well reproduced by shell model calculations [19]. These studies consider the (pf) orbitals for protons and the $(p, f_{5/2}, g_{9/2})$ orbitals for neutrons. The calculations also reproduce the experimentally determined orbital occupation numbers [20], predicting about 3.5 neutron holes in the (pf) shell which make GT_+ transitions possible. Fig. 2 compares the electron capture rates determined from the shell model and experimental GT ground state distributions. These rates do not include contributions from thermally excited nuclear states and hence correspond to stellar capture rates at finite temperatures only if one assumes that the GT_+ distributions are the same for all parent states (often called Brink's hypothesis). For comparison also the SMMC/RPA capture rates are shown. These rates are smaller than the others at smaller temperatures indicating that the model is not completely capable to resolve the strength distribution at low excitation energies. The agreement gets significantly improved at the larger temperatures (and densities) at which the SMMC/RPA model is used to predict stellar capture rates.

The shell model results for *fd* shell nuclei [10] and the SMMC/RPA results for heavier nuclei [16] have been combined for a compilation of electron rates 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