Weak-interaction processes during stellar collapse

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Massive stars end their lifes as type II supernovae, triggered by a collapse of their central iron core with a mass of more than $1M_\odot$. The general picture of a core-collapse supernova is probably well understood and has been confirmed by various observations from supernova 1987A. Nevertheless, the most sophisticated supernova simulations [1, 2, 3] currently fail to explode indicating that improved input or numerical treatment is required. Among these microscopic inputs are nuclear processes mediated by the weak interaction, where recent progress has been made possible by improved many-body models and better computational facilities. Our research focussed on the electron capture on nuclei and on inelastic neutrino-nucleus reactions.

In recent years we have calculated electron capture rates for many nuclei present during the collapse [4]. The calculations were based on modern many-body theories (diagonalization shell model or Shell Model Monte Carlo) and have been performed for the density and temperature conditions appropriate for the core collapse of a massive star. Importantly our research showed that electrons are captured on nuclei rather than on free protons during the entire collapse phase until neutrino trapping and thermalization is achieved [5]. Supernova simulations, using the improved electron capture rates, have strongly modified collapse trajectories (density, temperature, Y_e profiles, where Y_e is the electron-to-nucleon ratio). In particular, the shock wave is created at smaller radii with more overlying stellar mass, but travels slightly further out due to modifications of the ram pressure [6].

Electron captures reduce the Y_e values. As a consequence, the abundant nuclei become more neutron-rich and heavier, as nuclei with decreasing Z/A ratios are more bound in heavier nuclei. Nuclei are in nuclear statistical equilibrium during the collapse phase guaranteed by sufficiently fast reactions mediated by the strong and electromagnetic interaction. With increasing temperature and density, more nuclei are abundant in the collapsing core and contribute to the total electron capture rate. We have therefore extended our calculation of the rates to a larger number of nuclei (about 300). Furthermore we have tested approximate methods to investigate strategies to include even larger numbers of nuclei in our evaluations.

Due to the energy exchange in inelastic neutrino-nucleus reactions, this process can help to thermalize neutrinos after trapping during the collapse phase. However, this reaction is currently not included in supernova simulations. To overcome this shortcoming we have studied inelastic neutrino-induced reactions on more than 50 nuclei in the iron mass range [7]. Our calculations are based on the diagonalization shell model for the allowed (Gamow-Teller) transitions and on the Random Phase approximation for forbidden transitions. During collapse the neutrino energies are relatively small (order 10 MeV) and allowed transitions dominate. As the spin part of the isovector M1 operator is proportional to the Gamow-Teller operator, it has been possible to validate the shell model calculations of the allowed transitions by detailed comparison to high-precision M1 data, obtained in electron scattering experiments (Fig. 1) [8]. Our calculations have been summarized as a table which gives the inelastic neutrino-nucleus cross sections as function of initial and final neutrino energies and for the relevant supernova temperatures. Fig. 2 shows typical neutrino-induced cross sections on nickel isotopes for selected temperatures.

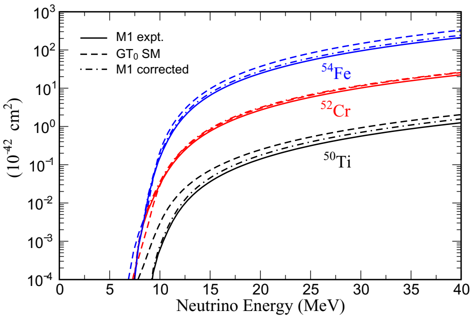

Figure 1: Neutrino-nucleus cross sections calculated from the M1 data (solid lines) and the shell-model GT_0 distributions (dotted) for ^{50}Ti (multiplied by 0.1), ^{52}Cr, and ^{54}Fe (times 10).

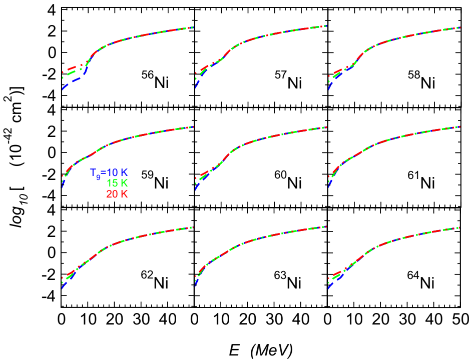

Figure 2: Cross sections for inelastic neutrino scattering on nuclei at finite temperature. The temperatures are given in MeV (from [7]).

References

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