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The role of electron capture in core-collapse supernovae

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Abstract

Electron captures on nuclei play an important role in the dynamics of the collapsing core of a massive star that leads to a supernova explosion. After the discovery of the importance of this mode by Bethe, Brown, Applegate and Lattimer and the pioneering work to derive individual nuclear capture rates by Fuller and collaborators, more recent calculations of these capture rates were based on microscopic models which account for relevant degrees of freedom and agree well with the relevant experimental data. Incorporated into supernova simulations the modern capture rates lead to important changes in the collapse dynamics. In particular, it became clear that electron capture on nuclei dominates over the one on free protons during the entire collapse until neutrino trapping.

Keywords: Supernovae; Electron capture; Shell model

1. Introduction and Gerry's role

"The theory of electron capture has gone a full circle and a half." With this statement Hans Bethe summarized the role of electron capture in his Review of Modern Physics article [1]. In fact, it started with the famous work of Gerry Brown together with Hans Bethe, Jim Applegate and Jim Lattimer (known as BBAL) who observed that 'electrons are captured by nuclei, the capture on free protons being negligible in comparison' [2]. This observation was based on the then recently discovered fact that Gamow–Teller (GT) transitions, which dominate stellar electron

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captures, are concentrated in relatively strong transitions, the GT resonance, at low excitation energies in the daughter nucleus. Having the Independent Particle Model (IPM) picture of ^{56}Fe in mind, Gerry Brown and his collaborators approximated the GT contribution to the capture rate by a single transition in which an $f_{7/2}$ proton is changed into an $f_{5/2}$ neutron. Discussing the effect of electron capture on the collapse of a massive stars, the authors of Ref. [2] conclude that 'the electron capture increases entropy, firstly because it occurs in matter that is not in beta equilibrium, and secondly because electron captures lead to excited states of the daughter nuclei which decay then to the ground state, mainly by γ-emission. However, escaping neutrinos will carry off a large fraction of the entropy.' In fact, it is the legacy of BBAL's work that the entropy stays low during the collapse and that, consequently, protons reside in heavy nuclei rather being set free by dissociation.

The Gamow–Teller strength distribution depends on individual nuclear structure effects. Hence in particular during the presupernova evolution (with densities up to about 10^{10} g/cm^3) the electron chemical potential is of the order of the nuclear Q-values (a few MeV) and electron capture rates depend on an accurate description of the GT strength distribution. The pioneering work to derive a set of individual electron capture rates for nuclei with mass numbers $A = 20$–60 has been derived by George Fuller and collaborators [3–6]. These authors based their rates on the IPM, however, supplemented by experimental data whenever available.

2. Electron capture within the diagonalization shell model

As stellar electron captures populate states in the daughter nucleus which are experimentally not accessible in atomic electron captures, the relevant GT_+ distributions[1] have to be derived by other means. Here one exploits the fortunate fact that the cross section of charge-exchange experiments at forward angles and at moderately high energies is proportional to the Gamow-Teller strength distribution. The pioneering work to measure GT_+ strength functions has been performed at TRIUMF using (n, p) reactions, achieving, however, only modest energy resolutions [7]. This situation has been dramatically improved by the development of the (d, ^{2}He) technique at the KVI Groningen which allowed to determine GT_+ distributions for many nuclei in the iron-nickel mass range with an energy resolution of about 150 keV [8].

The experimental data clearly show that the GT_+ strength is quenched with respect to the IPM estimate and strongly fragmented. Hence, indicating that nuclear correlations, beyond the mean-field approach, are essential for an accurate description of the GT strength. Furthermore, the finite temperature in the star requires the implicit consideration of capture on excited nuclear states, for which the GT_+ distribution can be different than for the ground state. Due to advances in soft- and hardware, the diagonalization shell model has been developed into the method of choice to describe nuclear properties in intermediate-mass nuclei, including spectra and transition strengths at low energies [9]. At first, Oda et al. derived detailed electron capture rates for nuclei in the mass range $A = 21$–40 based on shell model diagonalizations in the complete sd shell [10]. These studies have then been extended to the nuclei with mass numbers $A = 45$–65 which dominate the electron capture rate under the conditions of the late burning and early collapse stages. These (and other reaction rates mediated by the weak interaction) have been determined

[1] The subscript refers to the isospin component in the GT operator such that in GT_+ transitions a proton is changed into a neutron, in GT_- transitions, relevant for β decay of nuclei with neutron excess, a neutron is changed into a proton, and the GT_0 strength, important to describe low-energy inelastic neutrino–nucleus scattering, refers to transitions between proton states and neutron states, respectively.