Role of ^{55}Co in supernova explosions

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The complex dynamics of core collapse of massive stars is claimed to be greatly influenced by electron captures on ^{55}Co. The capture rates are calculated over a wide temperature (0.01×10^9 – 30×10^9 K) and density (10–10^{11} g cm^{-3}) domain using the proton-neutron quasiparticle random phase approximation (pn-QRPA) theory. The calculations show differences with the reported shell model diagonalization approach calculations and are comparatively enhanced at presupernova temperatures. The enhancement in rates is mainly attributed to the fact that this microscopic calculation is the first of its kind taking into consideration contributions from a lot many parent excited states. The so-called Brink's hypothesis is not assumed leading to more realistic estimate of the electron capture rates on ^{55}Co.

I. INTRODUCTION

Weak interactions play a conclusive role in the evolution of massive stars at the presupernova stage and lead to supernova explosions. These explosions mark the end of the life of massive stars. The energy budget would be balanced in favor of an explosion by a smaller precollapse iron core mass. Electron capture by free protons and by nuclei plays a key role in neutronisation of the core material and affects the formation of heavy elements above iron via the r-process at the final stage of the supernova explosion.

Nabi and Rehman [1] calculated the electron capture rates on ^{55}Co using the pn-QRPA model. This model was also successfully employed for the calculation of stellar weak rates for other important iron-regime nuclides [2-4] as well as for sd-shell nuclides [5]. The pn-QRPA theory [6-8] has been shown to be a good microscopic theory for the calculation of beta decay half lives far from stability [8,9]. The pn-QRPA theory was also successfully employed in the calculation of β^+/electron capture half lives and again satisfactory comparison with the experimental half-lives were reported [10]. The pn-QRPA theory was then extended to treat transitions from nuclear excited states [11]. In view of success of the pn-QRPA theory in calculating terrestrial decay rates, Nabi and Klapdor used this theory to calculate weak interaction mediated rates and energy losses in stellar environment for *sd*- [12] and *fp/fpg*-shell nuclides [13]. Reliability of the calculated rates was also discussed in detail in [13]. There the authors compared the measured data of thousands of nuclides with the pn-QRPA calculations and got good comparison (see also [14]). The main advantage of using the pn-QRPA theory is that one can handle large configuration spaces, by far larger than possible in any shell model calculations. In these calculations parent excitation energies well in excess of 10 MeV (compared to a few MeV tractable by shell model calculations) are included. Furthermore a large model space up to *7* major shells was considered in this work.

II. RESULTS AND DISCUSSIONS

The weak decay rate from the *i*th state of the parent to the *j*th state of the daughter nucleus is given by

$$\lambda_{ij} = \ln 2 \frac{f_{ij}(T,\rho,E_f)}{(ft)_{ij}} \tag{1}$$

where $(ft)_{ij}$ is related to the reduced transition probability B_{ij} of the nuclear transition by $(ft)_{ij} = D/B_{ij}$. D is a constant and B_{ij}'s are the sum of reduced transition probabilities of the Fermi and GT transitions. The phase space integral (f_{ij}) is an integral over total energy and for electron capture it is given by

$$f_{ij} = \int_{w_1}^{\infty} w\sqrt{w^2-1}(w_m+w)^2 F(+Z,w)G_- dw \,. \tag{2}$$

In the above equation, w is the total energy of the electron including its rest mass, and w_l is the total capture threshold energy (rest + kinetic) for electron capture. $G_-(G_+)$ is the electron (positron) distribution function.

The number density of electrons associated with protons and nuclei is $\rho Y_e N_A$ (ρ is the baryon density, and N_A is Avogadro's number).

$$\rho Y_e = \frac{1}{\pi^2 N_A}\left(\frac{m_e c}{\hbar}\right)^3 \int_0^{\infty} (G_- - G_+) p^2 dp \,. \tag{3}$$

Here $p = (w^2 - 1)^{1/2}$ is the electron momentum and the equation has the units of mol cm^{-3}. This equation is used for an iterative calculation of Fermi energies for selected values of ρY_e and T. Details of the calculations can be found in [12]. Experimental data, wherever available, was also incorporated to strengthen the reliability of the rates. In the calculations, the partial rates were summed over 200 initial and as many final states (to ensure satisfactory convergence) to get the total capture rate. For details refer to [13].

Realizing the pivotal role played by ^{55}Co for the core collapse, Langanke and Martinez-Pinedo also calculated these electron capture rates separately [15]. They used the shell model diagonalization technique in the *pf* shell. Due to model space restrictions and number of basis states involved in their problem, [15] performed the calculation only for two excited states (2.2 MeV and 2.6 MeV) along with the ground state.

The electron capture rates for ^{55}Co are shown in Fig. 1. The temperature scale T_9 measures the temperature in 10^9 K and the density shown in the legend has units of g/cm^3. These rates were calculated for densities in the range 10 to 10^{11} g/cm^3. Fig. 1 shows results for a few selected density scales. The figure depicts that for a given density, the electron capture rates remain, more or less, constant for a certain temperature range. Beyond a certain shoot off temperature the electron capture rates increase approximately linearly with increasing temperature. This rate of change is independent of the density (till 10^7 g cm^{-3}). For higher density, 10^{11} g cm^{-3} (density prior to collapse), one notes that the linear behavior starts around T_9 = 10.0. The region of constant electron capture rates, in the figure, with increasing temperature, shows that before core collapse the beta-decay competes with electron capture rate. At later stages of the collapse, beta-decay becomes unimportant as an increased electron chemical potential, which grows like $\rho^{1/3}$ during infall, drastically reduces the phase space. This results in increased electron capture rates during the collapse making the matter composition more neutron-rich. Beta-decay is thus rather unimportant during the collapse phase due to the Pauli-blocking of the electron phase space in the final state.

The comparison of the pn-QRPA calculations and the shell model approach [15] is shown in Fig. 2. Here the right panel shows the rate of [15]. The pn-QRPA rates are depicted in the left panel. These calculations were performed for the same temperature and density scale as done by [15]. ρ_7 implies density in units of 10^7 g cm^{-3} and T_9 measures temperature in 10^9 K.

For ^{55}Co, pn-QRPA rates are much stronger and differ by almost two orders of magnitude at low temperatures as compared to those of [15]. At higher temperatures the rates are still a factor of two more than those of [15].

What implications do these rates have on the dynamics of core collapse? The nuclei which cause the largest change in Y_e are the most abundant ones *and* the ones with the strongest rates. Incidentally, the most abundant nuclei tend to have small rates (they are more stable) and the most reactive nuclei tend to be present in minor quantities. The calculation here certainly points to a much more enhanced capture rates as compared to those given in [15]. The electron capture rates reported here can have a significant astrophysical impact. According to the authors in [16], $\dot{\Psi}_e$ (rate of change of lepton-to-baryon ratio) changes by about 50% due to electron capture on ^{55}Co. It will be very interesting to see if these rates are in favor of a prompt collapse of the core. Authors in [17,18] do point towards the fact that the spherically symmetric core collapse simulations, taking into consideration electron capture rates on heavy nuclides, still do not explode because of the reduced electron capture in the outer layers slowing the collapse and resulting in a shock radius of slightly larger magnitude. Currently work is in progress of finding the affect of inclusion of these rates in stellar evolution codes. The results are expected soon and will then be reported.

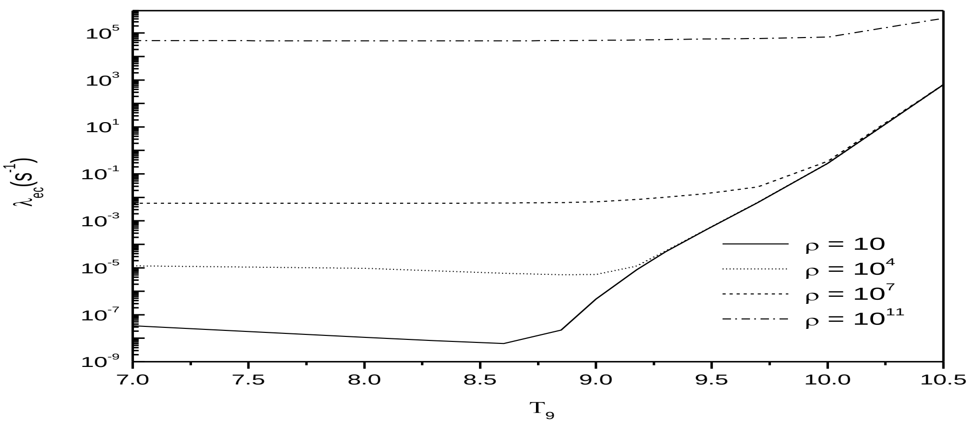

FIG. 1. Electron capture rates on ^{55}Co as function of temperature for different selected densities. For units see text.

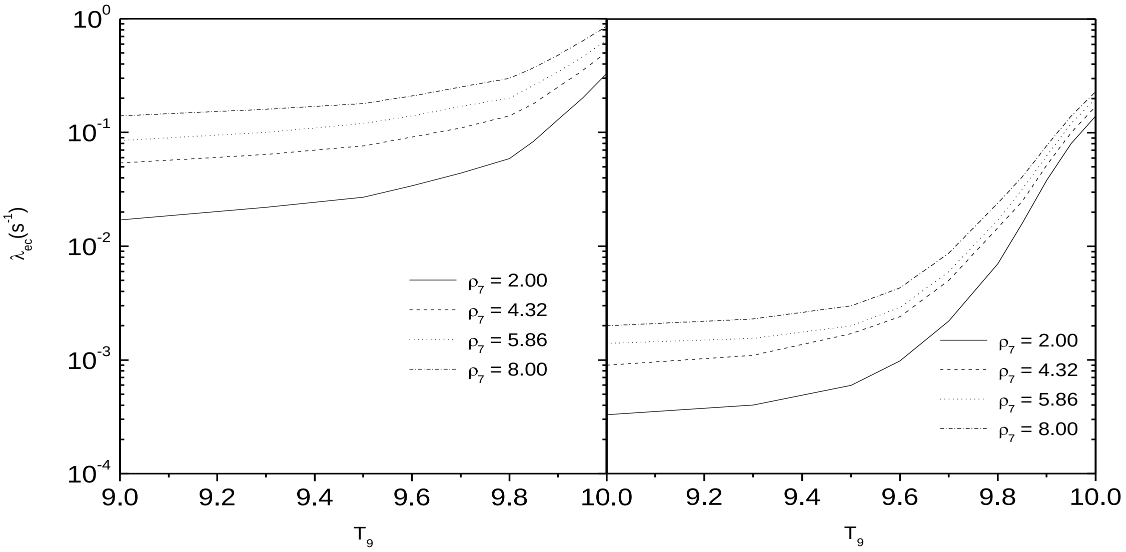

FIG. 2. Electron capture rates on ^{55}Co as function of temperature for different densities (left panel). The right panel shows the results of [15] for the corresponding temperatures and densities. For units see text.

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