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The Roles of Nuclear Physics during Stellar Core Collapse

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Nuclear physics plays an important role during the collapse of a massive star and the subsequent Type II or Ib/c supernova. Of particular importance during core collapse and the initial evolution of the supernova shock are nuclear electron capture and the nuclear equation of state. The nuclear equation of state (EoS) controls the nature of the bounce which initially forms the supernova shock while electron capture alters the nuclear and leptonic composition, determining the location where the shock forms. There is a strong interplay between nuclear electron capture and the nuclear equation of state, as the rate of electron capture depends on the nuclear composition determined by the EoS, while the EoS is sensitive to the neutronization set by the weak interactions. We summarize recent progress in three investigations into the role of Nuclear Physics during core collapse. We explore the impact weak interactions with heavy nuclei have in supernovae across the range of supernova progenitors. We demonstrate that these effects are sensitive to variations in the electron capture rates at the level of their current uncertainty. Finally, we present simulations showing the impact of changes in the nuclear equation of state on supernova shock formation and propagation.

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1. Introduction

Advances in nuclear structure theory have allowed a more realistic treatment of electron capture in supernovae to be developed [1]. With this new treatment of electron capture on heavy nuclei, Hix et al. [2] and Langanke et al. [3] have established that core collapse is strongly affected when electron capture on heavy nuclei is not suppressed, as it has been in supernova models for the last two decades. In a similar fashion, advances in nuclear physics are fostering the development of new prescriptions for the Equation of State, using a wide variety of methods and nuclear interactions. Studies to date of the impact of such EoS changes have produced ambiguous results.

This paper details three investigations into the role of Nuclear Physics during core collapse. These investigation use BOLTZTRAN, a three-flavor multigroup Boltzmann neutrino transport solver [4, 5], coupled with AGILE, a general relativistic spherically symmetric hydrodynamic solver which uses adaptive grid methods [6].

2. Effects of Nuclear Electron Capture across the Range in Progenitors

Hix et al. [2] used a Saha-like NSE together with recent shell model electron capture rates [7] for $45<A<66$ and 80 reaction rates from hybrid shell model-RPA calculations [3] (covering a sample of nuclei with $66<A<112$) to examine the impact of electron capture in a 15 $M_{\odot}$ model. This improved treatment of nuclear electron capture had two competing effects. In lower density regions, where the average nucleus is below N=40, electron capture on heavy nuclei can proceed in the Bethe et al. [8] picture. Here the long standard Bruenn parameterization[9] results in more electron capture than our improved treatment. In denser regions, the continuation of electron capture on heavy nuclei alongside electron capture on protons results in more electron capture in the new models. We here use the same prescription to examine the impact in a 25 $M_{\odot}$ model, where higher entropy results in a significant contribution from electron capture on protons during the later stages of stellar evolution [10]. The 9% reduction in the electron fraction in the interior of the PNS seen in the 25 $M_{\odot}$ case is somewhat smaller than the 15 $M_{\odot}$ case (12%), resulting in a smaller change in the mass of homologous core (.05 $M_{\odot}$ instead of .09 $M_{\odot}$), making a successful explosion more difficult to achieve, since each additional .1 solar mass of iron requires $\sim 10^{51}$ ergs to dissociate. Reductions in the central density (12%) and entropy (3%) at bounce, are also comparable to, but smaller than, those seen in the 15 $M_{\odot}$ case (17% and 6% respectively). The slowing of the collapse of the outer layers is also present in the 25 $M_{\odot}$ case, though also reduced from the 15 $M_{\odot}$ case. Thus the effects of the continuation of electron capture on heavy nuclei in the inner core is similar across the range of supernova progenitors, launching of a weaker shock with more of the iron core overlying it and slowing of the collapse of the outer core, in spite of higher initial entropy in more massive stars.

3. Uncertainties in the Nuclear Electron Capture Rate

Previous work has not addressed the impact of uncertainties in the rates for nuclear electron capture. We have examined the sensitivity of the models to such uncertainties with a parameter study taking (for simplicity and reproducibility by other groups) the Bruenn prescription as a starting point. Instead of letting the product of the number of protons in the $f_{7/2}$ level and the number

PoS(NIC-IX)117

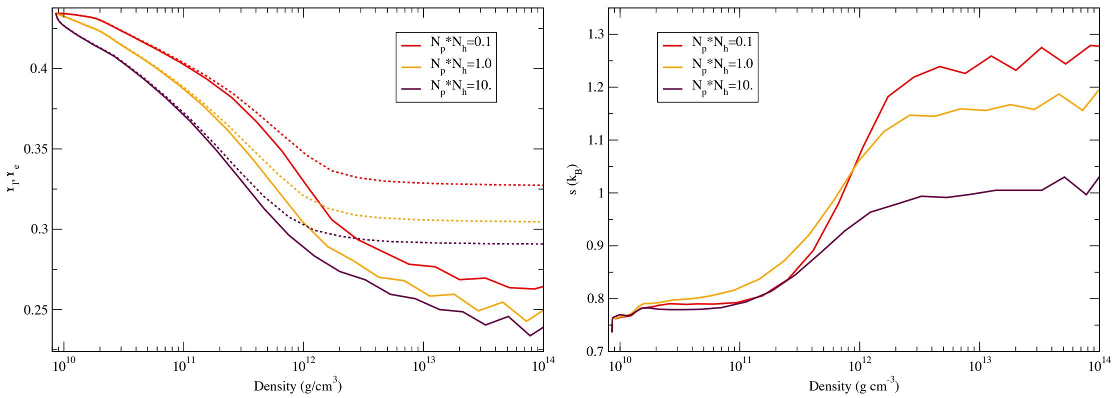

Figure 1: Evolution of the electron and lepton fractions (left) and entropy (right) with increasing density in a central zone of a collapsing 15 $M_{\odot}$ star.

of neutron holes in the $f_{5/2}$ level of the average nucleus (N_pN_h) vary as determined by the EoS, we set this product to several constant values in Newtonian collapse simulations. We find a reduction in the nuclear electron capture rate by a factor of 10 from those used by Hix et al. [2] would erase the changes demonstrated above. Likewise, a systematic increase by a factor of 10 would further reduce the initial PNS mass by an additional 10%. Even global changes of a factor of 2-3, the confidence factor usually assigned to the better known shell model diagonalization rates, would have significant consequences.

The differences in the evolution of the electron fraction and entropy for a central zone can be seen in Figure 1 for models with the product N_pN_h=0.1, 1.0 and 10.0. The entropy rise reflects the equilibration between the matter and the neutrino field. Higher entropies are reached in models where capture on protons, which emit higher energy neutrinos than nuclear captures, play a larger role. All models show a fairly uniform decrease in the lepton and electron fractions between densities of 10^{10} to 10^{12} g cm^{-3}, by which point a significant trapped neutrino fraction blocks further deleptonization. As a result, captures on a wide range of nuclei from A=60-100 contribute. Continued evolution of the electron fraction at higher densities is due to changes in the balance between neutrinos and electrons and is largely independent of the capture rates. The result is that each factor of 10 change in the electron/neutrino capture rates on heavy nuclei produces $\sim$ 30% additional deleptonization or a 10% lower Y_l. This weaker than linear proportionality between the electron capture rate and the lepton fraction is due to Pauli blocking. A higher electron capture rate leads to larger neutrino abundances, enhancing blocking of latter electron captures. Figure 2 shows the nuclear emissivity with and without blocking for the N_pN_h =0.1 1.0 and 10.0 cases. A clear proportionality is evident between the rate of nuclear electron capture and the amount of blocking. However, even in the N_pN_h =10.0 case, the blocking factor at 10^{12} g cm^{-3} is greater than 1/20.

4. The Impact of the Nuclear Equation of State

The collapse of the stellar core is ultimately halted when the nuclear potential becomes repulsive, causing the core to rebound, launching the prompt or bounce shock. The point at which this

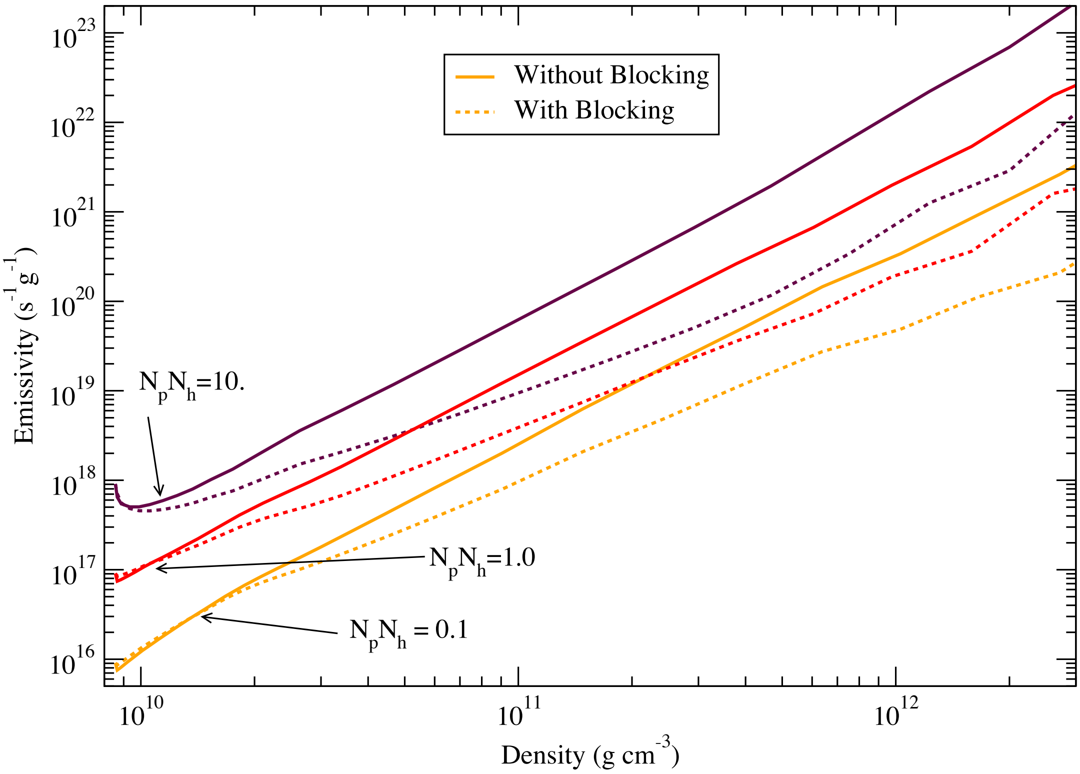

Figure 2: Evolution of the electron capture rate with increasing density in a central zone of a collapsing 15 $M_{\odot}$ star. Three cases are shown with N_pN_h =0.1, 1, 10. The dashed lines include the effects of Pauli blocking on the emitted neutrinos while the solid lines show the unblocked rate.

occurs and the strength of the shock are determined by the Equation of State (EoS). We have undertaken a program to examine the effects of the nuclear EoS. Figure 3 compares the results of two EoS: the compressible liquid drop EoS of Lattimer & Swesty [11] and the relativistic mean field EoS of Shen et al. [12] showing the propagation of the shock as a function of time for our simulations. Our results for shock propagation reveal a difference of 20 km 200 ms after bounce. The early behavior, especially the significantly earlier peaking of the Shen et al. case, is comparable to the results of Janka et al. (2004), however the faster decline of the Lattimer & Swesty case seen by these authors develops more slowly in our models. Simulations employing General Relativity and the LMSH electron capture prescription are in progress.

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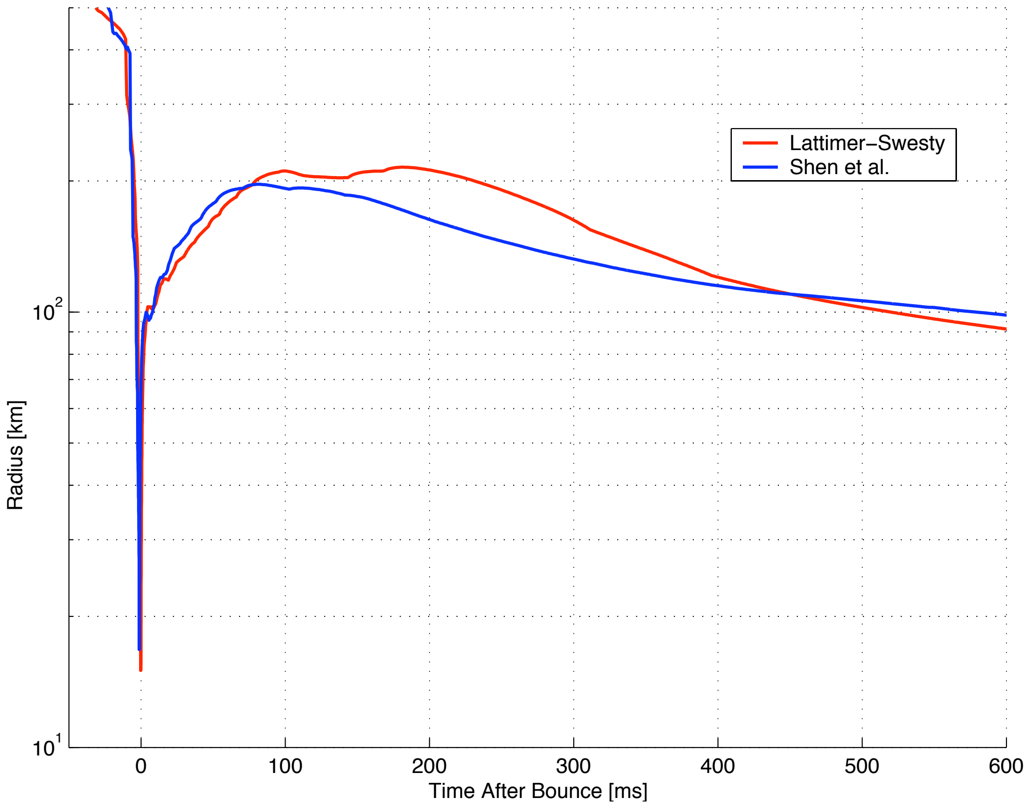

Figure 3: Comparison of the progress of the supernova shock for Newtonian models of 15 $M_\odot$ models using the Lattimer & Swesty [11] and Shen et al. [12].

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