Terascale input physics: the role of nuclear electron capture in core collapse supernovae

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Abstract. Core Collapse supernovae are among the most energetic explosions in the Universe and the predominant source of chemical elements heavier than carbon. They drive matter to extremes of density and temperature that cannot be produced on Earth and serve as laboratories for fundamental physics. Understanding these events requires the partnership of nuclear and particle physicists with astrophysicists and computational scientists. A case in point is the study of the role that captures of electrons and neutrinos on atomic nuclei play during the collapse of the core of a massive star as it reaches the end of its life. In addition to the astrophysical modeling, the required understanding of the structure of the atomic nucleus is itself a terascale application. We will discuss recent work which shows that a realistic treatment of electron capture on these nuclei causes significant changes in the hydrodynamics of core collapse and bounce, which set the stage for the subsequent evolution of the supernova.

1. Introduction
Four decades of research into core collapse supernovae has produced a model for these extremely luminous events that begins at the end of the life of a star more than ten times more massive than the sun. Successive stages of nuclear burning leave the star’s core composed of iron, surrounded by strata of successively lighter nuclei. This iron core of the star grows due to silicon burning in a shell at its edge, until it is too large to be fully supported by pressure from degenerate electrons. With insufficient pressure support and no additional energy available from further nuclear fusion, the core collapses rapidly. The inner portion of this iron core remains in sonic contact, collapsing homologously, with the outer portions trailing behind, falling supersonically. When the collapsing homologous core reaches densities like those of the nucleons in a nucleus, the repulsive core of the nuclear force renders the core incompressible, suddenly halting the collapse. Collision of the supersonically falling overlying layers with this stiffened core produces the \textit{bounce shock}, which drives these layers outward. This bounce shock is sapped of energy by
the escape of neutrinos and nuclear dissociation and stalls before it can drive off the envelope of the star.

The failure of this prompt supernova mechanism sets the stage for the neutrino reheating mechanism, wherein the intense neutrino flux, which is carrying off the $10^{53}$ erg binding energy of the newly formed proto-neutron star, heats matter above the neutrinospheres and reenergizes the shock. Under this paradigm, the shock remains an accretion shock until sufficiently reenergized to overcome the ram pressure of the infalling matter, whereupon it propagates outward, heating and transmuting the overlying layers and ejecting the envelope. While the neutrino reheating paradigm is widely considered to be the supernova mechanism, many simulations fail to produce explosions. This includes both spherically symmetric [1, 2, 3] and two dimensional models [4, 5, 6], leading to a variety of suggestions for vital pieces of physics that have been omitted or miscalculated. One such weakness in the current generation of models is incomplete treatment of interactions between atomic nuclei and electrons or neutrinos.

Of particular importance is the capture of an electron on an atomic nucleus, which changes one of the protons in the nucleus into a neutron and releases a neutrino. By destroying an electron, these interactions reduce the pressure supplied by the degenerate electron gas and accelerate the collapse of the stellar core. The release of the neutrino, which may escape or interact with matter in other regions of the star, changes the entropy of the matter, further affecting the hydrodynamic behavior. Finally, the behavior of nuclear matter at high densities is quite dependent on the ratio of protons (which experience a Coulomb repulsion due to their charge) to neutrons (which do not). This affects the strength of the bounce shock and subsequent supernova evolution. While calculation of the rate of electron capture on free protons is straightforward, the grouping of protons into nuclei greatly complicates the behavior because of collective effects. Of particular importance is the grouping of the nucleons in the nucleus into levels or shells. As is the case for electrons in an atom, filled nuclear shells result in much smaller reaction rates. In the case of atoms, it is shell structure that is responsible for the inertness of the noble gases. In the case of nuclei, our knowledge of the full impact of the shell structure continues to improve.

2. Electron Capture during Stellar Collapse

Bethe et al [7] pointed out that, due to the low entropy of the stellar core and resulting dominance of heavy nuclei over free nucleons, electron capture processes on heavy nuclei would dominate the evolution of the electron fraction during the late stages of stellar evolution and stellar core collapse. In the iron core, this predominantly occurs via Gamow-Teller (GT) transitions changing protons in the $1f_{7/2}$ levels into neutrons in the $1f_{5/2}$ level. However, it was soon realized that as core collapse proceeds, increasing neutronization and density lead to average neutron numbers $> 40$, filling the neutron $1f_{5/2}$ orbital and quenching further electron capture on heavy nuclei. Calculations using the independent particle model (IPM) showed that neither thermal excitations nor forbidden transitions substantially alleviated this blocking [8, 9]. However, it is well known that the residual nuclear interaction (beyond the IPM) mixes the $fp$ and $gds$ shells, for example, making the closed $g_{9/2}$ shell a magic number in stable nuclei ($N = 50$) rather than the closed $fp$ shell ($N = 40$). Full shell model diagonalization calculations remain computationally intractable in this regime due to the large number of available levels in the combined $fp + gds$ system[10]. Langanke et al [11] developed a “hybrid” scheme, employing Shell Model Monte Carlo (SMMC) calculations of the temperature-dependent occupation of the various single-particle orbitals to serve as input to Random Phase Approximation (RPA) calculations for allowed and forbidden transitions to calculate the capture rate. Even these “hybrid” models require several quadrillion floating point operations for each nucleus studied. With this approach, Langanke et al [12] (LMS) were able to demonstrate that electron capture on heavy nuclei dominates the capture on protons throughout core collapse.

To investigate the role played by electron capture on nuclei in altering the electron fraction and
entropy, and thereby determining the structure of the star and, in particular, the strength and location of the initial supernova shock, a new prescription was needed for nuclear electron capture in core collapse simulations. In most recent supernova simulations the treatment of nuclear electron capture introduced by Bruenn [13] is employed. The nuclear structure is approximated by the product of 2 terms, \( N_p \), the number of valence protons in the \( 1f_{7/2} \) level, and \( N_h \), the number of holes in the \( 1f_{5/2} \) neutron level. It is \( N_h \to 0 \) that quenches electron capture on heavy nuclei, allowing electron capture on protons to dominate the most important phases of core collapse in simulations using this prescription. To replace this prescription, we have developed a modern treatment, which we term the LMSH prescription, combining shell model electron capture rates from Langanke & Martínez-Pinedo [10] (LMP) for nuclei with 45-65 nucleons with the LMS reaction rates for 80 nuclei with 66-112 nucleons.

The adoption of modern electron capture rates has two competing effects, shown in Figure 1. In lower density regions, where the average nucleus is well below the \( N = 40 \) cutoff of electron capture on heavy nuclei, the Bruenn parameterization results in more electron capture than the LMP shell model rates provide. In denser regions, the dominance of electron capture on heavy nuclei over electron capture on protons results in more electron capture in the LMSH case. Hix et al [14] demonstrated that for a 15 solar mass progenitor, the improved electron capture prescription (principally the LMS rates) markedly reduced (\( \sim 10\% \)) the electron fraction in the interior of the PNS, resulting in an \( \sim 20\% \) reduction in the mass of the homologous core. At bounce, this change in the homologous core manifests itself as a reduction in the mass interior to the formation of the shock from 0.57 M\(_\odot\) in the fiducial case to 0.48 M\(_\odot\) in the LMSH case. The LMSH case also exhibits a \( \sim 15\% \) reduction in the central density and a \( \sim 5\% \) reduction in the central entropy at bounce, as well as an \( \sim 15\% \) smaller velocity difference across the shock. This results in the launch of a weaker shock with more of the iron core overlying it, inhibiting a successful explosion.

However, changes in the behavior of the outer layers also play an important role in the ultimate fate of the shock. The lesser neutronization in the outer layers (resulting from the LMP rates) slows the collapse of these layers, which further diminishes the growth of the electron
Figure 2. The neutrino luminosity and root-mean-square energy (at 500 km) as a function of time from bounce for a 15 $M_\odot$ model. The lines show this evolution for a simulation using the Bruenn (thin) and LMSH (thick) parameterizations. The solid lines correspond to electron type neutrinos, the dashed lines correspond to electron type antineutrinos.

capture rate by reducing the rate at which the density increases. Reductions of a factor of 5 in density and 40% in velocity are found in the regions outside of the homologous core. Such changes reduce the ram pressure opposing the shock, easing its outward progress. In these general relativistic, spherically symmetric models, these improvements allow the shock in the LMSH case to reach 168 km, relative to 166 km in the fiducial case. Thus the lesser electron capture in the outer layers can more than compensate for the greater mass overlying the shock when it was launched and the greater loss of energy to the neutrino burst. The final balance of these effects will need to be investigated with multi-dimensional models.

Figure 2 shows the luminosity and mean energy of the emitted electron neutrinos and antineutrinos between 100 milliseconds before bounce and 100 milliseconds after bounce. Clearly evident in the luminosity is a slight delay (2 ms) in the prominent “breakout” burst caused by the deeper launch of the shock in the LMSH case. Over the first 50 milliseconds after bounce, the LMSH model emits $\sim 15\%$ more energy than the fiducial model, with a slightly lower luminosity at later times. This is largely the result of differences in the mean electron neutrino energy, which is as much as 1 MeV higher over the first 50 milliseconds in the LMSH case, but lower thereafter. This results from the neutrinospheres in the LMSH model occurring in deeper, hotter layers for the first 50 milliseconds, but cooler layers at later times. The differences in the neutrino spectrum during collapse, when electron capture on nuclei dominates, are larger than those described after bounce. For low densities, where capture on nuclei dominates in the Bruenn prescription as well, the approximate reaction Q-value derived from the free neutron and proton chemical potentials dramatically underestimates the Q value, resulting in a much lower mean neutrino energy. As captures on protons begin to compete with captures on nuclei in the Bruenn prescription, the mean neutrino energy grows rapidly because of the higher Q value for capture on protons. It exceeds that found in our LMSH model by as much as 2 MeV in the 30 milliseconds just before bounce.
3. The Future
To examine the sensitivity of the models to uncertainties in the nuclear electron capture rates, we have conducted a parameter study. For simplicity (and reproducibility by other groups), we have taken the Bruenn prescription as a starting point. Instead of letting the product $N_pN_h$ vary as determined by the EOS, we have set this product to several constant values and run Newtonian collapse simulations. From these studies, we see that a reduction in the total electron capture rate by a factor of 10 from those predicted by Langanke et al [12] would erase the changes demonstrated by Hix et al [14]. Likewise, a systematic increase by a factor of 10 would further reduce the initial PNS mass by at least 10%. Even changes at lesser levels would significantly alter the location of shock formation, therefore further efforts to verify these rates, both theoretical and experimental, are necessary. The large number of nuclei which participate in the electron capture render these models insensitive to errors in individual reactions, however systematic errors, particularly for unstable nuclei with $A > 65$ that dominate electron capture during the most important phases, could be important.

This work demonstrates the necessity of cross-disciplinary research on the core collapse supernova problem. The ability of femtometer scale, nuclear structure physics to affect the dynamics of the supernova at the kilometer scale requires expertise at both of these scales, merging together two terascale problems. By drawing on our combined expertise in nuclear astrophysics and nuclear structure physics, we have demonstrated that electron capture on heavy nuclei is a vitally important process in core collapse supernovae. Further improvements in this area will require continued alliance between these sub-fields as well as continued access to leading computational capabilities.

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