# Yields in Simple Models of Dense Thermonuclear Supernovae

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**Introduction:** FUN CAIs and hibonite grains show roughly correlated excesses and deficits in the neutron-rich iron-group isotopes, such as $^{48}$Ca and $^{50}$Ti (e.g., [1] and references therein). Such findings seem to correspond to correlation of these isotopes in the precursor dust of these inclusions in the early Solar System. This conclusion aligns with nucleosynthesis theory since the neutron-rich iron-group isotopes are abundantly co-produced in low-entropy expansions of neutron-rich matter [2], which presumably occur in rare Type Ia (thermonuclear) supernovae. The abundances of these isotopes in such expansions, however, depends on how neutron-rich the material gets, which in turn depends on the complex nuclear dynamics during the supernova. We are developing and releasing computational tools to model these astrophysical events. We here describe the yields of the neutron-rich isotopes from our models.

**Nuclear Network:** To compute the nucleosynthesis in thermonuclear supernovae, one needs a nuclear reaction network and the relevant nuclear rates. For our reaction network, we use libnucnet [3]. For reaction rates, we use the JINA reaclib database [4]. To compute weak interaction rates on nucleons and nuclei, we supplement the detailed weak rate compilations of [5,6] with a simple rate parameterization [7]. Our routines for these parameterized weak interaction rates are available in our open-source module NucNet Tools [8].

**Thermodynamics:** To compute simple models of dense Ia supernova, we have written several thermodynamics libraries. First we released libstatmech [9], which allows us to compute the thermodynamics of fully relativistic, fully degenerate ideal matter. We have built a number of routines to compute energy and entropy generation from nuclear reactions and related thermodynamic quantities. We also constructed routines to compute simple radiation transport and neutrino energy loss. These are included in NucNet Tools [8].

**Simple Ia Model:** We have constructed a computer code to compute a simple model of a Type Ia supernova. The exploding white dwarf is treated as a uniform sphere. All gradients of quantities are replaced by the ratio of that quantity divided by the radius of the sphere. While the macroscopic aspects of the model are extremely simplified, the microscopic effects, i.e. the thermodynamic and the reaction network, are treated in full detail. This allows us to gain a good idea of the details of the nuclear dynamics in a realistic but simple thermonuclear supernova model.

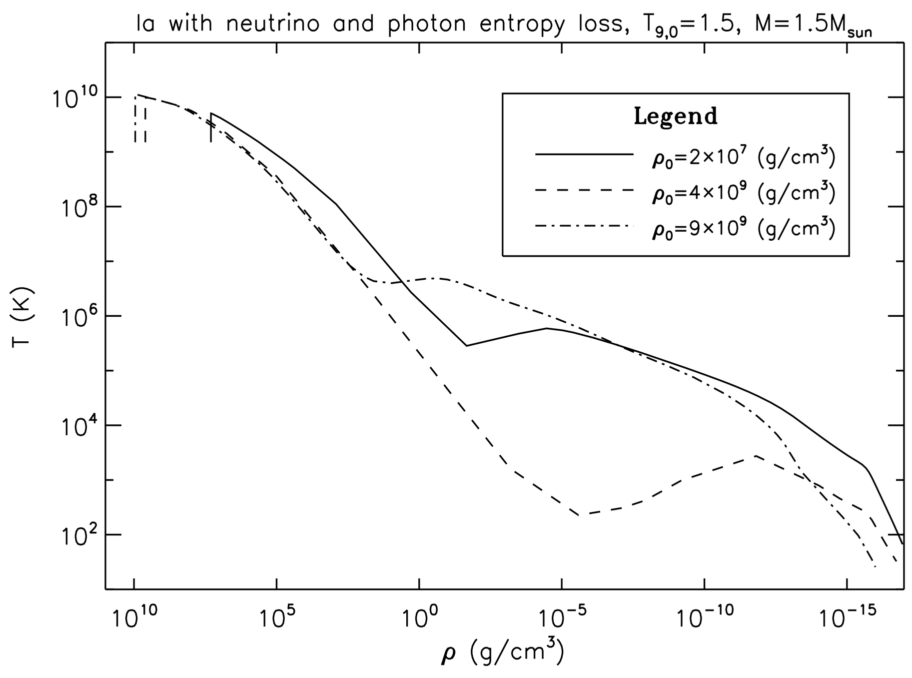


**Fig. 1**. Temperature versus density in a simple Type Ia supernova model for different initial densities.

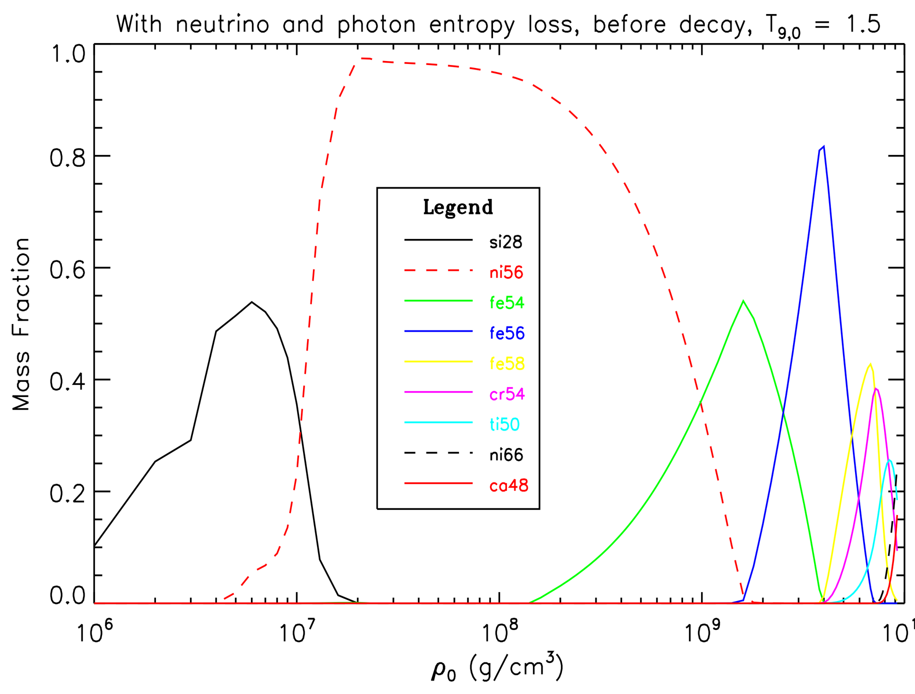


**Fig. 2**. Mass fractions of selected species versus initial density of a simple Type Ia supernova model.

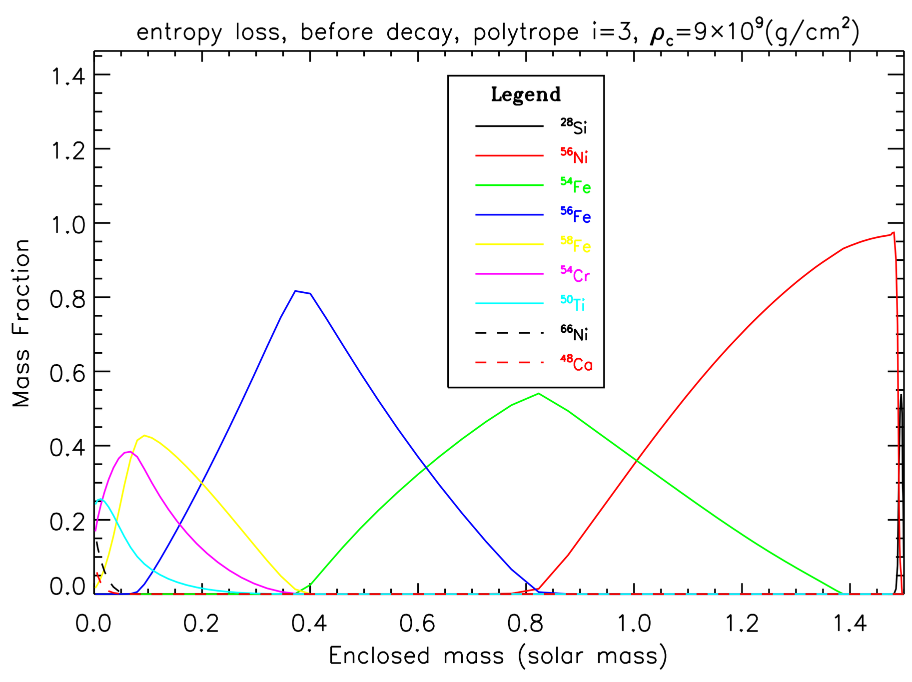


**Fig. 3**. Yield mass fractions of selected species versus enclosed mass of a white dwarf with polytrope index of 3 and initial central density of 9×10$^9$ g/cm$^3$.

**Fig. 1** shows the temperature change with density in expansions for various initial density inputs. The uniform white dwarfs began at a temperature of 1.5 billion K, a mass of 1.5 solar masses with 50% $^{12}$C and 50% $^{16}$O in mass. For high initial density cases (4×10$^9$ and 9×10$^9$ g/cm$^3$), the white dwarf stays at a high temperature before the star can respond to the pressure built up and start to expand. Then the radioactivity begins to reheat the material. For the calculation with initial density of 2×10$^9$ g/cm$^3$ the resulting large abundance of radioactive $^{56}$Ni produced in the supernova (refer to Fig. 2.) will decay to $^{56}$Co and then to $^{56}$Fe to release energy and reheat the ejecta once it attains a density of ~0.01 g/cm$^3$. For the initial density of 4×10$^9$ g/cm$^3$ the most abundant production is of stable $^{56}$Fe. It is interesting to note that $^{54}$Cr and $^{50}$Ti are both stable isotopes; thus, material in which they dominate the abundances will tend to have less radioactive reheating than ejecta in which $^{48}$Ca is abundant since the latter also includes abundant radioactive $^{66}$Ni.

**Fig. 2** shows the yields of our simple Type Ia model as a function of different initial densities. At high densities, more neutron-rich isotopes are produced because of the greater degree of electron capture occurring during the explosion. Beyond some critical density (about 9.2×10$^9$ g/cm$^3$ in this calculation), electron capture reduces the pressure so much in the initial stages of the event that the white dwarf collapses instead of expanding (see, for example, [10]).

**Fig. 3** shows the yield of a Type Ia supernova with initial central density of 9×10$^9$ g/cm$^3$. We use a polytrope to simulate the structure of the white dwarf. We use the data in Fig. 2. as the input for each mass zone of the white dwarf to compute the yields. In central zones there are large quantities of neutron-rich iron-group isotopes, like $^{54}$Cr, $^{50}$Ti, $^{48}$Ca. If there is a chance for them to condense or coat on to existing dust grains together, it may help explain the correlation described in Introduction.

**Conclusions**: Although our astrophysical model is quite simple, it gives results that are in reasonable agreement with detailed models (e.g. [11]). We find that neutron-rich iron-group isotopes can be produced and might condense together during the explosion of such dense Ia supernovae. The results of this work will feed into chemical condensation calculations and Galactic chemical evolution models in an effort to understand the isotopic effects in precursor dust of FUN CAIs and hibonites.

**References:** [1] Meyer B. S. and Zinner E. in Me- teorites and the Early Solar System II (Tucson: Univer- sity of Arizona Press), p.69-108. [2] Meyer B. S. et al. 1996. Astrophys. J. 462:825-838. [3] See http://sourceforge.net/projects/libnucnet [4] See http://groups.nscl.msu.edu/jina/reaclib/db/ [5] Fuller G. M. et al. 1985. Astrophys. J. 293:1-16. [6] Langanke K. and Martínez-Pinedo G. 2000. Nucl. Phys. A 673:481-508. [7] Arcones A. et al. 2010. Astron. Ap. 522:A25. [8] http://sourceforge.net/projects/nucnet-tools [9] http://sourceforge.net/projects/libstatmech. [10] Baron, E. et al. Astrophys. J. 320:304-307. [11] Woosley S. E. 1997. Astrophys. J. 476:801-810.