YIELDS IN SIMPLE MODELS OF DENSE THERMONUCLEAR SUPERNOVAE. Tianhong Yu[1] and Bradley S. Meyer[2], [1]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA, tyu@clemson.edu, [2]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA, mbradle@clemson.edu.

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. We also explore the outflow thermodynamics and some consequences for dust condensation.

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 from [7]. The detailed weak rates in general are preferable to the simple parameterization but do not cover the full range of nuclei needed. 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.

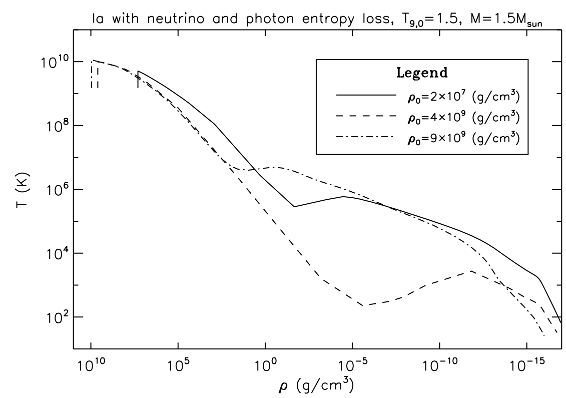

Fig. 1. Temperature versus density in a simple Type Ia supernova model for different initial densities.

Results: Fig. 1 shows the temperature change with density in expansions for various initial density inputs. Since the white dwarf expands with time, decreasing density on the abscissa corresponds to increasing time. The uniform white dwarfs began at a temperature of 1.5 billion Kelvins, a mass of 1.5 solar masses with 50% ^{12}C and 50% ^{16}O in mass. The temperature rises sharply at the beginning. Here the carbon buring and oxygen buring heat up the material and lead the system to a nuclear statistical equilibrium (NSE) via a quasi-equilibrium (QSE). For high initial density cases (4×10^9 and 9×10^9 g/cm^3), electron captures then will release more energy and drive the material neutron rich. The white dwarf stays at a high temperature before the star can respond to the pressure built up and start to expand. The cooling curves follow a $\rho \sim T^3$ line at first as a gas dominated by radiation and soon move to a $\rho \sim T^{3/2}$ line as a matter-dominated classical gas would behave. 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. Likewise ^{66}Ni will help reheat the ejecta in the model with initial density of 9×10^9 g/cm^3. For the initial density of 4×10^9 g/cm^3 the most abundant production is of stable ^{56}Fe. Thus the material will cool down to a low temperature of a few hundreds Kelvins before some minor radioactive species start to contribute to the reheating. 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.

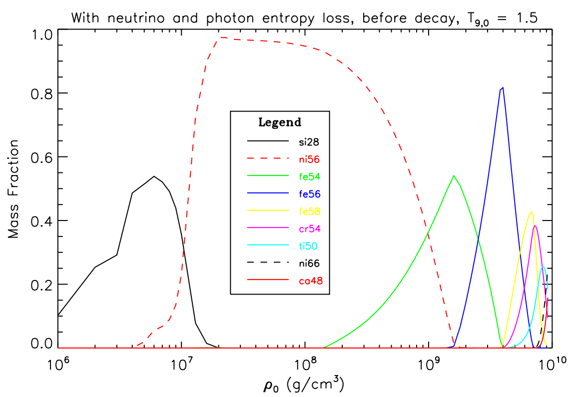

Fig. 2. Mass fractions of selected species versus initial density of a simple Type Ia supernova model.

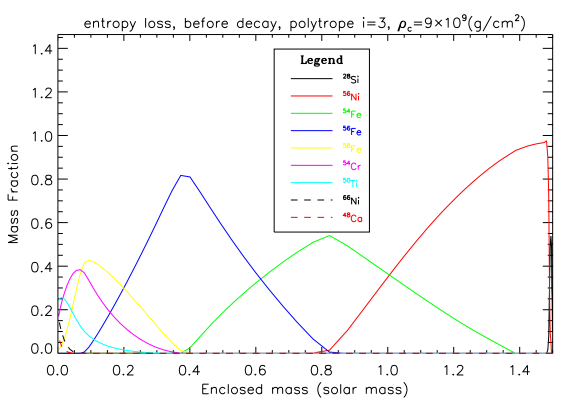

Fig. 3. Yield mass fractions of selected species versus enclosed mass of a white dwarf with polytrope index of 3 and initial central density of 9×10^9 g/cm^3.

Fig. 2. shows the yields of our simple Type Ia model as a function of different initial densities. All the calculations have the same initial temperature, mass and initial mass fractions as above. At high densities, more neutron-rich isotopes are produced because of the greater degree of electron capture occurring during the explosion. For a uniform white dwarf with a density of 9×10^9 g/cm^3, a large amount of ^{48}Ca and ^{50}Ti would be produced together, each counts almost 20% of the total mass. 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. In such a case, the star would eventually explode as an "accretion-induced" collapse (AIC), which is similar to a regular Type II (core-collapse) supernova (see, for example, [10]). Ejecta from AIC's will typically be characterized by high entropy, like the ejecta from Type II events, so we do not expect significant production of neutron-rich iron-group isotopes from them. Note that we that plotted the radioactive isotopes with dashed line in Fig. 2.

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. A polytropic index = 3 calculation gives a good fit to the structure as compared to our TOV solver for such a high density 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.

Conclusion: Although our astrophysical model is quite simple, it gives results that are in reasonable agreement with detailed models (e.g. [11]). This makes our model a good laboratory for studying the detailed microphysics in dense Ia supernova. 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 Meteorites and the Early Solar System II (Tucson: University 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.