ON PRODUCTION OF NEUTRON-RICH IRON-GROUP ISOTOPES IN SIMPLE MODELS OF DENSE THERMONUCEAR SUPERNOVAE. T. Yu and B. S. Meyer. Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA

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 effects seem to call for correlation of these isotopes in the precursor dust of the Solar System. From a nucleosynthesis point of view, this makes sense because the neutron-rich iron-group isotopes are copiously co-produced in low-entropy expansions of neutron-rich matter [2], which presumably occur in rare Type Ia (thermonuclear) supernovae. The production of these isotopes in such expansions, however, depends on how neutron-rich the material becomes, which in turn depends on the complicated nuclear dynamics during the supernova. We are developing and releasing computational tools to follow these dynamics. Here we present some results of a simple model of a dense thermonuclear explosion that nevertheless provides a reasonable picture of such events and their nucleosynthesis.

Nuclear Network: Computation of nucleosynthesis in thermonuclear supernovae requires a nuclear reaction network and relevant nuclear reaction 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 use a simple rate parameterization from [5]. While compilations of these weak rates exist [6.7], they do not extend neutron rich enough to ensure accurate calculation of the neutronization of the matter in the supernova explosion. 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 a number of thermodynamics libraries. We first have available libstatmech [9], which allows us to compute the thermodynamics of fully relativistic, fully degenerate ideal matter. We have also built a number of routines to compute energy generation from nuclear reactions and related thermodynamic quantities. 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 in 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, namely, the thermodynamics and the reaction network, are treated in full detail. This allows us to get a good idea of the details of the nuclear dynamics in a realistic but simple supernova model.

Results: Fig. 1 shows the temperature in billions of Kelvins in a representative calculation. The model began at a temperature of 1.5 billion Kelvins, a mass density of 4×10^9 g/cc, and an initial radius of 1,000 km. The initial composition is pure ^{12}C. As is apparent, the temperature rises sharply after about 30 microseconds. Here the ^{12}C begins burning. The initial spike up to 7 billion Kelvins is due to the fact that the matter first reaches a quasi-equilibrium (QSE) with too many heavy nuclei. This QSE relaxes to a nuclear statistical equilibrium (NSE) by disintegrating some of the heavy nuclei, which causes the temperature to drop. Once the NSE is achieved, the temperature rises due to energy released by electron captures, which drives the material neutron rich. The white dwarf stays at a high value until about 0.1 seconds, at which time the star can respond to the pressure build up and start to expand.

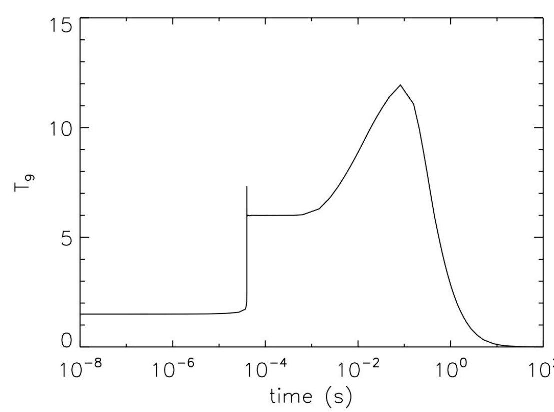

Fig. 1. Temperature in 10^9 K versus time in a simple Type Ia supernova model.

Fig. 2 shows the radius of the white dwarf relative to its initial radius during the calculation. The pressure build up from energy release by nuclear reactions causes the star to expand rapidly. Within 100 seconds, the star has expanded to greater that 100 times its initial radius. At this time, the velocity of the surface of the star has leveled off to its final value, which is ~1% the speed of light.

Fig. 3 shows the mass fraction of neutron-rich iron-group nuclides during the explosion. The reaction network stays in NSE until the temperature drops below 6 billion Kelvins at about 1 second. As the temperature falls from 6 billion to 4 billion Kelvins, the network remains in a quasi-equilibrium with an excess of heavy nuclei relative to NSE [2]. Finally, as the temperature drops further, reaction freezeout occurs and leaves a distribution of mass fractions dominated by the neutron-rich iron-group species.

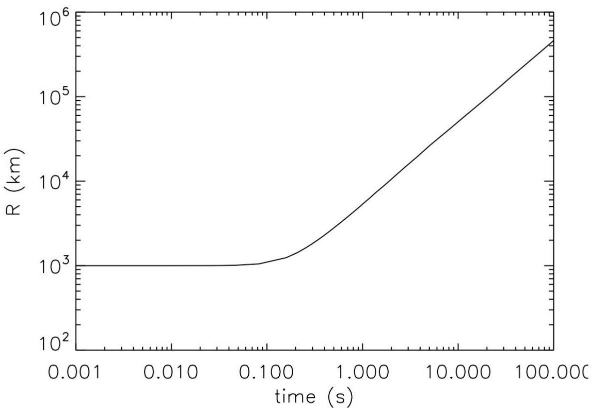

Fig. 2. Radius of the exploding white dwarf versus time in a simple Type Ia supernova model.

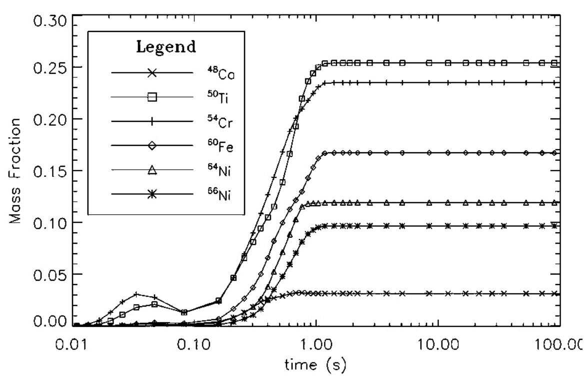

Fig. 3. The mass fraction of neutron-rich nuclides versus time in a simple SNIa model. These species comprise 90% of the ejected mass.

Conclusions: Although our astrophysical model is quite simple, it gives results that are in reasonable agreement with detailed models (e.g., [10]). This makes our model an excellent laboratory for studying the detailed microphysics in dense Ia supernova. We are exploring the sensitivity of our results to input microphysics. We are also working to release the simple Ia code as open-source software. In future work, we will incorporate our yields into Galactic chemical evolution models in an effort to understand the isotopic effects in 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] Arcones A. et al. 2010. Astron. Ap. 522:A25. [6] Fuller G. M. et al. 1985. Astrophys. J. 293:1-16. [7] Langanke K. and Martínez-Pinedo G. 2000. Nucl. Phys. A 673:481-508. [8] http://sourceforge.net/projects/nucnet-tools [9] http://sourceforge.net/projects/libstatmech. [10] Woosley S. E. 1997. Astrophys. J. 476:801-810.