NRLEE NUCLEOSYNTHESIS. B. S. Meyer[1], K. R. Bermingham[2,3], K. Frizzell[2], K. Mezger[4,5]. [1]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA (mbradle@clemson.edu); [2]Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08854, USA; [3]Department of Geology, University of Maryland, College Park, MD 20742, USA; [4]Institut für Geologie Universität Bern, Bern CH-3012 Switzerland; [5]Center for Space and Habitability, Universität Bern, Bern CH-3012 Switzerland.

Introduction: Isotopic anomalies in primitive meteorites likely arise from incomplete mixing of presolar carriers in the early proto-planetary disk. Correlated anomalies are present in ^{48}Ca and ^{50}Ti [1] and ^{54}Cr and neutron-rich nickel isotopes [2,3]. Interesting correlated anomalies in these isotopes and species like ^{84}Sr and ^{96}Zr also are present (e.g., [3]). We present some implications of these correlated anomalies in the LPSC 2021 abstract by Bermingham. In the present abstract, we present some details of a simple model of the nucleosythesis in the astrophysical event that might be important for production of these key isotopes—a NRLEE.

NRLEE: Production of abundant ^{48}Ca is known to occur only in freeze outs from neutron-rich, low-entropy quasi-equilibria (QSE) [4]. The low entropy allows more nuclei to be present in the QSE than would be present in a nuclear statistical equilibrium at the same temperature, density, and neutron richness and points to explosions of dense matter, such as may occur in deflagrations of dense C/O white dwarf stars [5], electron capture supernovae [6], or thermonuclear electron-capture supernovae [7]. We have generically termed such events NRLEEs (Neutron-Rich, Low-Entropy matter Ejectors) and have presented a possible structure of the initial ejecta from such events [8], which is most likely some kind of exploding white dwarf star.

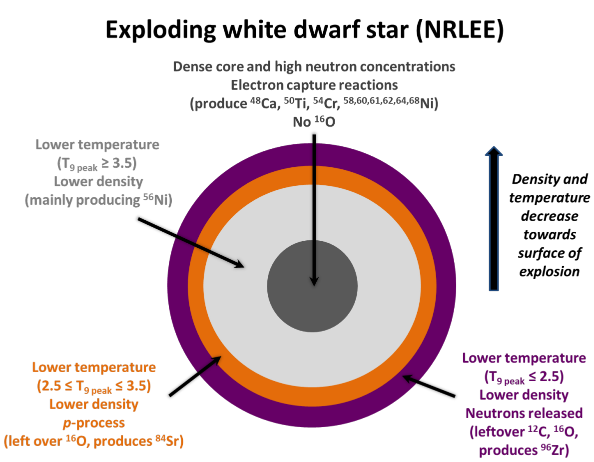

Fig. 1. Schematic nucleosynthetic structure of the ejecta from an exploding white dwarf star (a NRLEE).

Fig. 1 shows a schematic of the possible structure of the NRLEE ejecta right after the explosion of the star. The innermost regions are dense and can experience sufficiently strong electron capture to be driven neutron-rich enough to produce isotopes like ^{48}Ca. In the outer layers, where the initially abundant carbon and oxygen or oxygen, neon, and magnesium do not completely burn up, the peak temperatures and densities are lower, and neutron-induced reactions can occur and produce isotopes like ^{96}Zr abundantly [9]. In the hours, days, and weeks following the explosion, mixing between the inner and outer layers may allow for oxides or other condensates to form, which would then plausibly be the carriers that eventually give rise to the isotopic anomalies discussed above.

Nucleosynthesis: We modeled the possible ejecta from a NRLEE with nuclear reaction network calculation performed with NucNet Tools [10] based codes using the V2.2 JINA reaclib library [11]. To get the isotopic composition of the initial white dwarf star, we simulated hydrogen burning by running the network at a temperature $T_9 = T / 10^9$ K = 0.02 and a mass density 20 g/cc for 3 Gyr. The initial composition was the Solar composition from [12]. The hydrogen burning primarily converted the initial ^{1}H to ^{4}He and generated a large supply of ^{14}N from the initial carbon, nitrogen, and oxygen via CNO cycling.

We then ran helium burning at $T_9 = 0.2$ at a mass density of 1000 g/cc for 200,000 years using the ashes from our hydrogen burning calculation as the initial composition. This converted the abundant initial ^{4}He into ^{12}C and ^{16}O. It also converted the ^{14}Ne into ^{22}Ne.

To simulate the s-process nucleosynthesis that would have occurred during the He shell burning during the star's AGB phase, we ran calculations using the output from the helium burning calculation at T_9=0.3 and mass density 1000 g/cc. We set a constant neutron density of 10^8 per cc and ran the calculation for 200,000 years. We kept track of the neutron exposure and then averaged abundances according to an exponential distribution of exposures with average exposure of 0.3 inverse millibars, which gives a reasonable representation of the Solar System's main s-process abundance distribution [13]. The final abundances of this calculation were assumed to be the initial composition of the exploding white dwarf star.

To model the nucleosynthesis in the outer layers of the exploding white dwarf, we assumed that the density expanded exponentially on a 1 second timescale, and we assumed the density varied with the cube of the temperature. We ran calculations with the peak temperature ranging from T_9=0.1 to 4.

During the explosion of the outer layers of the white dwarf, abundant neutrons are liberated via the reaction $^{22}Ne(\alpha,\gamma)^{25}Mg$, which gives rise to a neutron burst. This produces abundant ^{96}Zr, as shown in Fig. 2. The initially abundant, lower-mass Zr isotopes quickly capture neutrons and become ^{96}Zr. The burst is so robust, some further neutron capture occurs and pushes some ^{96}Zr to $^{97,98}Zr$, but ^{96}Zr ends up by far the most produced stable Zr isotope.

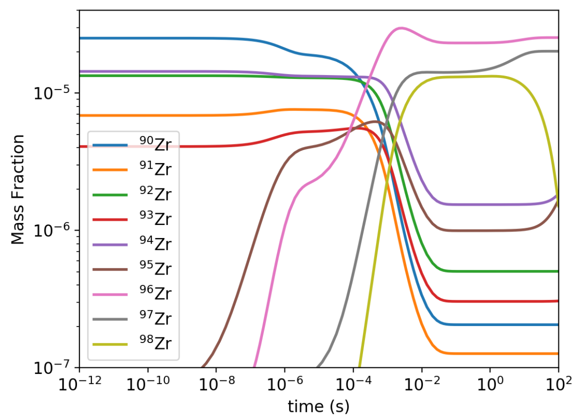

Fig. 2. The zirconium abundances as a function of time in an outer layer in the NRLEE that reaches a peak temperature T_9=0.8.

To model the nucleosynthesis in the inner layers of the exploding white dwarf star, we ran a set of calculations with varying initial density but initial temperature T_9=10 and an exponential expansion like the outer layers but with a timescale of 0.5 seconds. We supplemented the reaclib database with schematic weak rates [14]. This allowed the network to followed electron capture reactions that drive the matter neutron rich during the explosion.

Fig. 3 shows the elemental abundances at four times during the explosion. The times are indicated in the figure legend, along with the temperature T_9 and electron fraction at that moment. The electron fraction is the number of electrons per nucleon in the matter. By charge neutrality, the electron fraction is the number of protons per nucleon. At early times, the composition is dominated by the initial carbon and oxygen (with Y_e=0.5). By several milliseconds, the matter has attained nuclear statistical equilibrium with abundances dominated by Fe and Ni isotopes. At 0.026 seconds, the temperature has hardly declined, but the electron fraction has dropped to 0.45. The last curve in the figure shows the elemental abundances at 1.36 seconds, near the freeze out of the underlying QSE. The abundances are dominated by iron-group elements, with Ca and Ni most abundant, as expected in a QSE with Y_e near 0.42 [4].

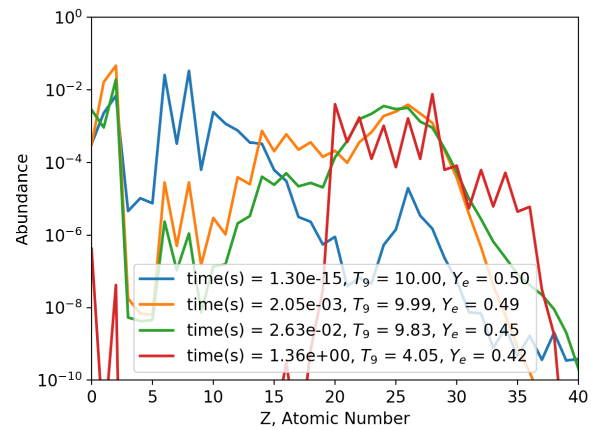

Fig. 3. Elemental abundances at four times in an inner layer of the NRLEE with initial mass density 8.51 x 10^9 g/cc.

Conclusions: This brief paper has shown some of the details of NRLEE nucleosynthesis, with an emphasis on the production of ^{96}Zr and neutron-rich iron-group species. As described previously [8], one expects mixing to occur in the explosion, which could condense grains that carry these isotopes together. Many more details from our calculations are available. The best way to explore these details is via the Jupyter Notebooks presented by us in the abstract by Frizzell. Those sufficiently interested can also run their own calculations by following the instructions at our GitHub repository [15].

References: [1] Dauphas, N. et al. (2014) *EPSL, 407,* 96-108. [2] Warren P. (2011) *EPSL, 311,* 93-100. [3] Burkhardt C. et al. (2019) *GCA, 261,* 147-170. 1344–1345. [4] Meyer, B. S. et al. (1998) *Astrophys. J. 498,* 808-830. [5] Woosley S. E. (1997) *Astrophys. J. 476,* 801-810. [6] Wanajo S. et al. (2013) *Astrophys. J. 767*, L26. [7] Jones S. et al. (2019) *Astron. Astrophys. 622,* A74. [8] Meyer B. S. et al. *LPSC 51,* 2652. [9] Travaglio C. (2011) *Astrophys. J.739,* 19. [10] http://sourceforge.net/p/nucnet-tools. [11] https://reaclib.jinaweb.org. [12] Lodders K. (2003) *Astrophys. J. 674:* 607-611. [13] Clayton D. D. And Ward R. A. (1974) *Astrophys. J. 193:*397:400. [14] Arcones A. et al. (2010) *Astron. Astrophys. 522:*A25. [15] https://github.com/mbradle/nrlee_lpsc2021.