EXPLODING WHITE DWARF STARS AND THE CARRIERS OF NUCLEOSYNTHETIC ISOTOPE ANOMALIES. B. S. Meyer[1] and K. R. Bermingham[2]. [1]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA (mbradle@clemson.edu), [2]Department of Geology, University of Maryland, College Park, MD 20742, USA (kberming@umd.edu).

Introduction: Correlated anomalies in ^{48}Ca and ^{50}Ti in a variety of solar system samples appear to call for a presolar carrier that couples those isotopes in a 1:1 ratio, possibly a perovskite ($CaTiO_3$) [1]. A similar correlation between ^{54}Cr and neutron-rich nickel isotopes suggests there is presolar carrier coupling those two isotopes (e.g., [2,3]). Given the correlation trend, we speculate that this is possibly a spinel ($NiCr_2O_4$). Interestingly, there are also correlations between these neutron-rich iron-group species and isotopes like ^{84}Sr and ^{96}Zr, especially in the NC vs. CC grouping (e.g., [3]). These correlations further suggest coupling of these isotopes in presolar carriers. In this short paper, we consider the possible nucleosynthetic site of the isotopes in these carriers and the possible condensation giving rise to them.

Nucleosynthesis: While most neutron-rich iron-group elements can be produced in the s process, especially in massive stars (e.g., [4]), ^{48}Ca cannot. This isotope must be produced in a low-entropy, neutron-rich environment [5]. Such environments may occur in deflagrations of dense C/O white dwarf stars [6], electron-capture supernovae [7], or thermonuclear electron-capture supernovae in O/Ne/Mg white dwarf stars [8]. The last of these is currently favored as the site for ^{48}Ca production, but whether it, or any of the currently proposed sites is the dominant source of the solar system's supply of ^{48}Ca remains to be established. What is clear is that some kind of ejection of neutron-rich matter from a white dwarf star is most likely responsible for the solar system's supply of ^{48}Ca and other neutron-rich iron-group isotopes, and we use the term NRLEE (Neutron-Rich Low-Entropy matter Ejector) to denote this astrophysical site generically.

The structure of the ejecta from a NRLEE is shown schematically in Fig. 1. Due to stellar evolution prior to the explosion, the initial composition of the white dwarf is typically some combination of ^{12}C, ^{16}O, ^{20}Ne, and ^{24}Mg. The inner region is dense enough to allow electron capture to occur during the explosion of the white dwarf star, which allows the matter to become neutron rich. Here isotopes such as ^{48}Ca, ^{50}Ti, ^{54}Cr, and the neutron-rich nickel isotopes are produced. In the light grey region in the figure, the peak temperature attained during the explosion is high, but the density is lower than in the core. Here the matter does not become neutron rich, so there is considerable production of ^{56}Ni and intermediate mass species such as ^{28}Si, but all of the initially present species burn to heavier nuclei. In the outer parts of the exploding star, the peak temperatures during the explosion are lower ($T_9 = T/10^9$ K < 3.5). Here not all the initially present nuclei burn. In these regions, there is also possible production of p-process species [9,10] and ^{96}Zr [10].

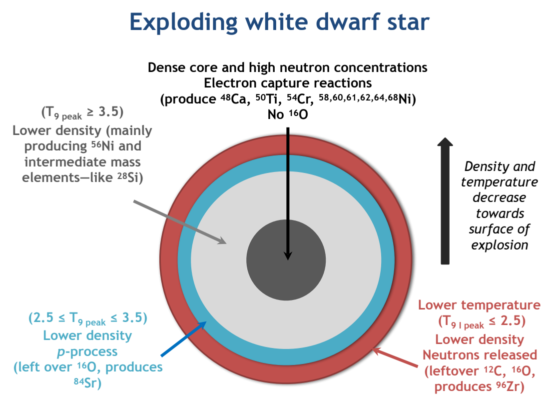

Fig. 1. Schematic nucleosynthetic structure of the ejecta from an exploding white dwarf star (a NRLEE).

To explore the nucleosynthesis from a NRLEE in more detail, we performed nuclear reaction network calculations with NucNet Tools [11]. Fig. 2 shows the mass fractions of species occurring in the core of the NRLEE as a function of initial density. The density decreases from the center of the white dwarf outwards. The calculations began with equal abundances of ^{12}C and ^{16}O. The initial T_9 was 10, and the matter was taken to expand and cool on 0.5 second timescale. The figure shows the mass fractions of species 100 seconds after the explosion. The highest density matter achieved the greatest degree of neutron richness due to electron capture. Calcium-48, ^{50}Ti, ^{54}Cr, and various neutron-rich nickel species are all abundantly produced in this region.

Fig. 3 shows the carbon and oxygen in the outer parts of the NRLEE. Here the network calculations took an initial density of 10^7 g/cc and varying initial T_9. The expansion timescale was again 0.5 s. For $T_9 > 3.5$, all the carbon and oxygen initially present is destroyed. At lower temperatures, ^{16}O survives and is even, in some zones, produced from ^{12}C by a combination of carbon and neon burning. At the lowest temperatures, even the initial ^{12}C remains unburned

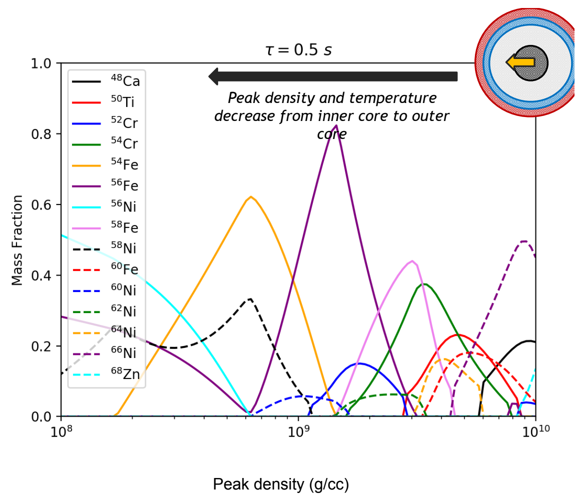

Fig. 2. The mass fractions of dominant species as a function of peak density in the NRLEE. The schematic shows where this nucleosynthesis occurs (cf. Fig. 1).

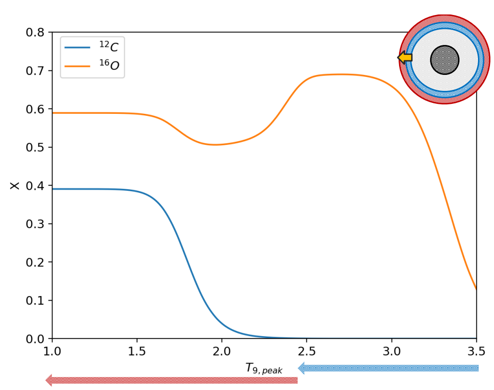

Fig. 3. The carbon and oxygen mass fractions in the outer layers of the exploded white dwarf star. The schematic shows where this nucleosynthesis occurs (cf. Fig. 1).

Due to presupernova stellar evolution, it is expected that some production of neutron source nuclei such as ^{13}C and ^{22}Ne can occur. During the presupernova stellar evolution, this gives rise to s-process nucleosynthesis. During the explosive nucleosynthesis in the outer regions of the NRLEE, the presence of neutron seeds leads to a burst of neutrons. We included such neutron seeds and s processing in our calculations and show some results in Fig. 4. At the highest temperatures, normal p-processing overwhelms this neutron burst and leads to strong overproductions of p-process isotopes such as ^{84}Sr. At lower temperatures, however, the neutron burst plays a role, leading to strong overproduction of ^{96}Zr.

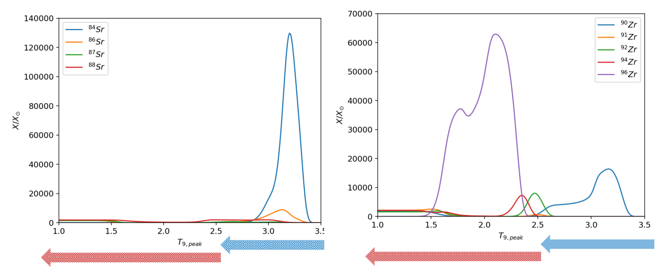

Fig. 4. Overproduction (resulting mass fraction relative to solar mass fraction) of ^{84}Sr (left panel) and ^{96}Zr (right panel) in the outer layers of a NRLEE. The red and blue arrows refer to the same regions as in Fig. 3.

Carriers: Condensation of putative perovskite and spinel carriers in a NRLEE obviously requires mixing of the dense core material (the dark grey region in Fig. 1), where the neutron-rich iron group species are produced, and the outer layers (the blue and red regions in Fig. 1) where abundant oxygen is present. The explosion of the white dwarf is expected to produce such mixing (e.g., [8]). Interestingly, the recently discovered ^{50}Ti- and ^{54}Cr-rich oxide presolar grains, which probably come from one or more NRLEEs, also suggest such mixing occurs [12]. Because of the strong overabundances of ^{84}Sr and ^{96}Zr in the oxygen-rich NRLEE matter, the carriers will likely contain strong enrichments in these isotopes. Variable incorporation of these carriers in different early solar system regions could then give rise to the nucleosynthetic anomalies seen in solar system samples in both the NC and CC regions.

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] Rauschet T. et al. (2002) *Astrophys. J. 576*, 323–348. [5] Meyer, B. S. et al. (1998) *Astrophys. J. 498*, 808-830. [6] Woosley S. E. (1997) *Astrophys. J. 476*, 801-810. [7] Wanajo S. et al. (2013) *Astrophys. J. 767*, L26. [8] Jones S. et al. (2019) *Astron. Astrophys. 622,* A74. [9] Howard W. M. et al. (1991) *Astrophys. J. 373*, L5. [10] Travaglio C. (2011) *Astrophys. J. 739*, 19. [11] http://sourceforge.net/p/nucnet-tools. [12] Nittler L. et al. (2018) *Astrophys. J. 854*, L24.