**NRLEE NUCLEOSYNTHESIS OF TITANIUM-46 AND ZIRCONIUM-95.** B. S. Meyer[1], K. R. Bermingham[2]. [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.

**Introduction:** Isotopic anomalies in neutron-rich, iron-group isotopes, such as $^{50}$Ti, $^{54}$Cr, and, especially, $^{48}$Ca, in a variety of planetary materials suggest the presence of dust in the early Solar System from rare astrophysical events that ejected neutron-rich, low-entropy matter [1,2]. The exact nature of these events is unclear, but they are likely associated with the explosion of a dense white-dwarf star, such as the deflagration of a near Chandrasekhar-mass white dwarf [3], an electron-capture supernova [4], or a thermonuclear electron-capture supernova [5]. Due to the variety of plausible sites, it is convenient to refer to them generically as NRLEEs (Neutron-rich, Low-Entropy matter Ejectors).

Owing to the special nucleosynthetic requirement that $^{48}$Ca be produced in expansions of neutron-rich, low-entropy matter [6], NRLEEs are the chief producer of $^{48}$Ca (and other neutron-rich, iron-group isotopes such as $^{50}$Ti and $^{54}$Cr) in the Galaxy, and, indeed, NRLEEs may be defined, at the most basic level, as those astrophysical events that produce $^{48}$Ca.

**Figure 1** shows the possible anatomy of a NRLEE. The innermost region of the exploding white-dwarf star is dense and undergoes significant electron capture during the thermonuclear explosion. This is where the neutron-rich, iron-group species, such as $^{48}$Ca, are made in the envisioned NRLEE scenario.

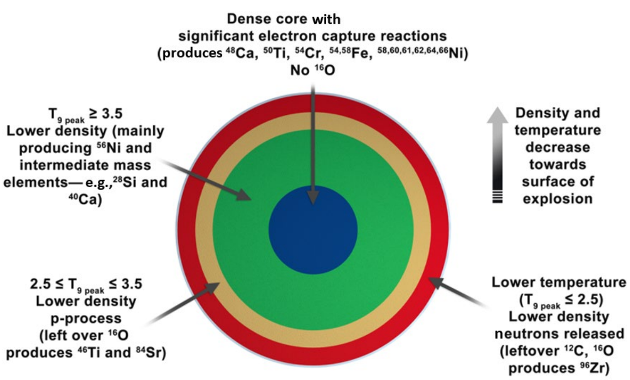


***Fig. 1.** Schematic giving details of the nucleosynthetic yields in the different regions of the NRLEE immediately after the explosion (figure from [1]).*

While the innermost regions of the NRLEE model in **Figure 1** experience the neutron-rich explosive nucleosynthesis important for production of $^{48}$Ca, the outer layers of the NRLEE may also have nucleosynthesis important for understanding isotopic anomalies. For example, significant production of $^{46}$Ti may occur in the layers undergoing incomplete explosive oxygen burning (that is, oxygen burning that does not completely consume the initial oxygen present), while layers reaching even lower peak densities and temperatures may undergo neutron-burst nucleosynthesis that produces $^{95}$Zr, which could then decay *in situ* to $^{95}$Mo in NRLEE dust.

**Titanium-46 and -50:** The correlated anomalies in $^{46}$Ti and $^{50}$Ti [7,8] in a variety of planetary samples is remarkable because these isotopes are considered to be produced in different nucleosynthetic processes: incomplete oxygen burning ($^{46}$Ti) and s processing or freezeouts from low-entropy, neutron-rich quasiequilibria ($^{50}$Ti). By virtue of their nucleosynthesis in two different stellar settings, it has been suggested that $^{46}$Ti and $^{50}$Ti are housed in different presolar grains in the early Solar System. If so, subsequent processing in the proto-planetary disk would be necessary to give rise to the correlated anomalies in Solar System-derived materials [7,8].

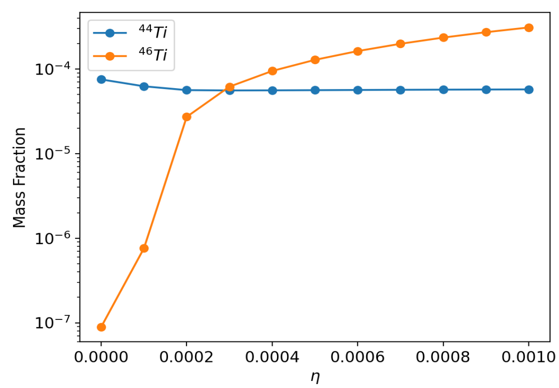


***Fig. 2.** Final mass fractions of $^{44}$Ti and $^{46}$Ti immediately after explosive oxygen burning as a function of neutron excess.*

A more straightforward explanation would include the coproduction of $^{46}$Ti and $^{50}$Ti in the same stellar event. Considering that NRLEE events produce $^{46}$Ti, the possible coproduction of $^{46}$Ti and $^{50}$Ti was investigated.

In the NRLEE model, if the pre-explosion white-dwarf star has some small neutron richness, as expected from the pre-explosion nuclear processing, oxygen burning may lead to significant production of $^{46}$Ti [9].

**Figure 2** shows the mass fractions of $^{44}$Ti and $^{46}$Ti immediately after explosive oxygen burning as a function of neutron excess $\eta$. The neutron excess is the excess number of neutrons in a system per nucleon. For example, for matter consisting entirely of $^{17}$O, the neutron excess would be (9-8)/17 = 1/17 = 0.06 since $^{17}$O has nine neutrons and eight protons. The calculations were run with the Webncleo single-zone reaction network. The matter began at initial $T_9 = T/10^9K = 3.3$ and mass density of $\rho = 1.3 \times 10^8 g/cc$. The density declined exponentially on a 0.1 second timescale. The initial composition was a combination of $^{16}$O and enough neutrons to give the indicated neutron excess.

As **Figure 2** shows, once there are more than about 0.0002 excess neutrons per nucleon, the final $^{46}$Ti mass fraction is significant, and even higher than that of $^{44}$Ti. No other titanium isotope is abundant in the resulting matter, although $^{48}$Cr, the parent of $^{48}$Ti is significantly produced.

The initial composition of the progenitor star of the white dwarf had an excess of protons, not neutrons. Upon completion of hydrogen burning, the initial protons (hydrogen) converted to $^4$He, which created matter with equal numbers of neutrons and protons. The hydrogen burning likely proceeded through CNO cycling, which dominantly put any initial C, N, and O isotopes into $^{14}$N. During subsequent helium (and perhaps carbon burning), which results in the C/O-rich or O/Ne/Mg-rich white dwarf star that eventually explodes, the $^{14}$N burned to $^{22}$Ne via the reaction $^{14}N + ^4He \rightarrow ^{18}F + \gamma$, where $\gamma$ represents photons carrying away energy from the reaction. The sequence then proceeded as $^{18}F \rightarrow ^{18}O$ and $^{18}O + ^4He \rightarrow ^{22}Ne$. The decay of $^{18}$F produced a small excess of neutrons in the matter. Matter with solar composition has roughly 1% of its mass in C, N, and O isotopes. This would correspond to about $7 \times 10^{-4}$ $^{14}$N nuclei per nucleon after CNO burning. Since each $^{14}$N nucleus converts to $^{22}$Ne, and since $^{22}$Ne has two excess neutrons, this is a neutron excess of $1.4 \times 10^{-3}$.

Lower initial metallicity than Solar would lead to lower neutron excess than $1.4 \times 10^{-3}$ (perhaps by a factor of two), but the outer layers of the exploding white dwarf star should have a neutron excess greater than 0.0002 and thus should significantly produce $^{46}$Ti in layers that undergo incomplete oxygen burning. Thus, these layers would be rich in unburned $^{16}$O and $^{46}$Ti. If a small amount of $^{50}$Ti from the inner layers mixed in with this matter, oxide dust is likely to condense that contained both $^{46}$Ti and $^{50}$Ti that could give rise to the observed correlated anomalies [7,8].

**Zirconium-95 and Mo isotopes**: Correlated isotopic anomalies in $^{94}$Mo and $^{95}$Mo are present in planetary materials, and, significantly, the correlation lines for NC and CC materials are offset from each other [e.g., 10]. The correlation lines are likely due to varying amounts of SiC grains incorporated by the planetary bodies, but the offset requires differing amounts of $^{94}$Mo or $^{95}$Mo in the NC and CC matter.

If the peak temperatures in the outer layers of the exploding white dwarf star reach values less than about $T_9 = 1.5$, any $^{22}$Ne unburned in the pre-explosion evolution of the star can undergo the reaction $^{22}Ne + ^4He \rightarrow ^{25}Mg + n$. The neutrons thus suddenly released may be captured by other species, including isotopes of Zr, in what is a type of neutron-burst nucleosynthesis. Such processing synthesizes interesting quantities of $^{96}$Zr [11]. It will also naturally produce a large abundance of $^{95}$Zr, with a half-life of 64 days. The seed abundances for the neutron-burst synthesis of $^{95}$Zr are likely enhanced by s processing in shell burning in the progenitor star.

Since the $^{95}$Zr-rich layers will also have abundant unburned $^{16}$O, it is likely that the $^{95}$Zr will condense into NRLEE oxide grains. The condensed $^{95}$Zr would then decay *in situ* to $^{95}$Mo. If Zr condensed preferentially to Mo, the NRLEE dust would likely be highly anomalous in $^{95}$Mo. Differing abundances of NRLEE dust in the NC and CC regions would then potentially give rise to differing NC and CC abundances of $^{95}$Mo, which could thus explain the offset in the NC and CC $^{94}$Mo-$^{95}$Mo anomaly correlation lines.

**Jupyter Notebooks:** Interested readers may wish to explore NRLEE nucleosynthesis in more detail via the interactive Jupyter Notebooks that the authors have constructed [12].

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**References:** [1] Bermingham K. R. et al. (*in rev.*) Geochim. Cosmochim. Acta. [2] Bermingham K. R. et al. LPS *53*, 1469. [3] Woosley, S. E. (1997) Astrophys. J. 476, 801-810. [4] Wanajo, S. (2013) *Astrophys. J. Lett. 767,* L26. [5] Jones S. et al. (2019) Astron. Ap. 622, A74. [6] Meyer B. S. et al. (1996) Astrophys. J. 462, 825-838.[7] Trinquier et al., (2009) Science 324, 374-376. [8] Davis,A. M. et al. (2018) *GCA 221,* 275-295. [9] Woosley S. E. et al. (1973) *Astrophys. J. Suppl. 26,*231-312. [10] Worsham E. et al (2017) *EPSL 467,* 157-166. [11] Travaglio, C. et al. (2011) *Astrophys. J. 739,* 93. [12] https://github.com/mbradle/NRLEE-Nucleosynthesis; https://webnucleo.readthedocs.io.