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Molybdenum Isotopes from a Neutron Burst

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MOLYBDENUM ISOTOPES FROM A NEUTRON BURST. B. S. Meyer, D. D. Clayton, L.-S. The, *Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978 (brad@photon.phys.clemson.edu, clayton@gamma.phys.clemson.edu, lihsin@keck.phys.clemson.edu).*

Introduction. The molybdenum isotopes in two silicon carbide X grains have been studied with resonant-ionization mass spectrometry (1). The resulting isotopic patterns are anomalous and quite puzzling. In particular, the grains show large excesses in ^{95}Mo and ^{97}Mo. Such an isotopic signature is distinctly different from the s-process pattern seen in the mainstream SiC grains in which ^{96}Mo and ^{98}Mo excesses prevail. It is also different from the expected r-process pattern for which the largest expected excess would be at ^{100}Mo. The X grain Mo isotopic patterns suggest a different origin for these isotopes than the classical s- and r-processes.

A possible alternative origin could be a neutron burst of the type proposed to explain the heavy xenon (Xe-H) isotopic patterns in microdiamonds (2-4). A 1992 quantitive study of that scenario considered the isotopic patterns that would be co-produced with Xe-H (5). Interestingly, the Mo isotopic pattern in that neutron-burst scenario shows largest excesses in ^{95}Mo and ^{97}Mo without a similarly large excess in ^{100}Mo. Such a pattern agrees well with that found in the SiC X grains.

In this brief paper, we seek to understand the nucleosynthetic origin of the ^{95}Mo and ^{97}Mo excesses in the neutron-burst scenario envisioned in (5). This will provide insight into its astrophysical context and the relevant nuclear physics.

The Calculations. We take as our basic model that presented in (5), namely, that the neutron burst occurs in shocked helium-rich matter in an exploding massive star. The nucleosynthesis code includes all relevant strong, electromagnetic, and weak interactions (6). In particular, it includes the relevant neutron-capture cross sections and beta-decay rates in the molybdenum region of the nuclide chart. As in (5), a solar distribution of nuclei is exposed to a weak neutron fluence ($\tau = 0.002$ mb) to mimic any weak s-processing in the presupernova phase of the star's life. To simulate the shock, we took the ashes of the weak s-processing to be at 1500 g/cc, an appropriate density, and heated it suddenly to $T = 10^9$ K. We took the matter to expand and cool on a 10 second hydrodynamical timescale. By the time the neutrons produced by the (α, n) reactions on nuclei such as ^{13}C and ^{22}Ne had all captured onto heavier isotopes, the final neutron exposure τ was 0.077 mb, in good agreement with the 0.075 mb exposure in (5).

Results. Fig. 1 shows the yttrium and zirconium isotopes before shock passage (dotted lines) and 200 seconds after the shock passage (solid lines). The neutron burst is so rapid that few beta decays occur; thus, by the end of the calculation, the neutron burst has caused many of the original ^{89}Y nuclei to neutron capture out to ^{95}Y, which has a low neutron-capture cross section and is therefore an isotope at which mass accumulates. Similarly, the pre-burst Zr pattern (dominated by ^{90}Zr) is transformed by the burst into one with largest mass fraction at ^{96}Zr, again due to its small cross section. The even-A isotopes of post-burst Zr are larger than their odd-A counterparts

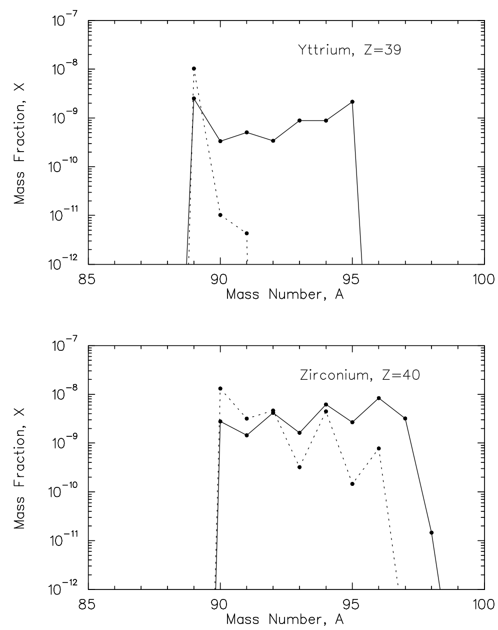

Figure 1: Mass fractions of Yttrium (upper panel) and Zirconium (lower panel) isotopes. The dotted lines show the pre-burst abundance distribution while the solid lines show the abundances 200 seconds after the burst.

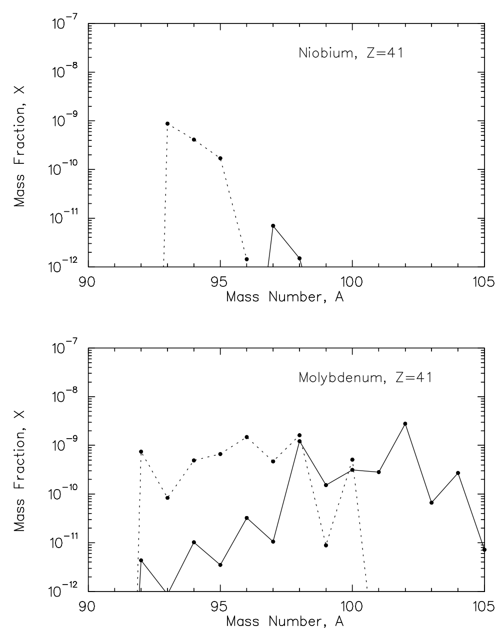

Figure 2: Mass fractions of Niobium (upper panel) and Molybdenum (lower panel) isotopes. The dotted lines show the pre-burst abundance distribution while the solid lines show the abundances 200 seconds after the burst.

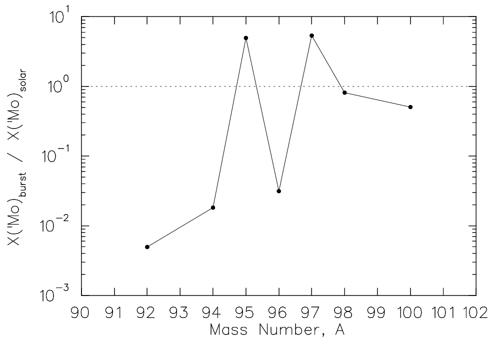

Figure 3: Final overabundances (mass fractions relative to solar) of the molybdenum isotopes after beta decay. The dominant excesses are ^{95}Mo and ^{97}Mo.

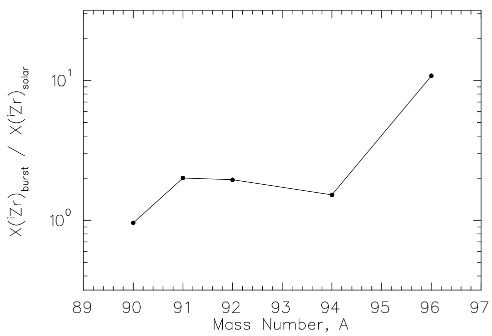

Figure 4: Final overabundances (mass fractions relative to solar) of the zirconium isotopes after beta decay. The dominant excess is at ^{96}Zr.

because the former have smaller cross sections. Importantly, however, the A=95 and A=97 isotopes are quite abundant. ^{100}Zr, on the other hand, is not present because there were too few neutrons released in the burst to allow neutron capture flow to reach that isotope. Interestingly, the small cross sections of the zirconium isotopes play the important role of retaining stable seed Zr through the burst so that its heavier isotopes can be enriched. This is in contrast to Mo (see below) where the large cross sections allow the neutron-capture flow to proceed beyond the heavy stable Mo isotopes.

Fig. 2 is similar to Fig. 1 except that it shows the isotopes of Nb and Mo. Nb is strongly depleted during the burst because neutron captures carry the original isotopes out to ^{98}Nb, where they rapidly beta decay to ^{98}Mo. Interestingly, the A=92-97 isotopes of Mo are all strongly depleted by the neutron burst as the bulk of the initially present Mo neutron captures out to A=102 and beyond. ^{98,99,100}Mo are all still present, but the first and third of these are slightly depleted from their initial values.

An mpeg movie showing the evolution of the mass fractions of the Y, Zr, Nb, and Mo isotopes may be seen at

http://photon.phys.clemson.edu/movies.html

Interestingly, the movie shows that the large ^{98}Mo abundance at 200 s after the burst results not so much from original Mo as from abundant ^{98}Zr, which decays on a $\sim$ 30 s timescale through ^{98}Nb to ^{98}Mo.

Fig. 3 shows the final overabundances (mass fractions relative to solar after beta decay). As is clear from the figure, the largest excesses relative to solar are at ^{95}Mo and ^{97}Mo.

Discussion The nucleosynthetic origin of the ^{95,97}Mo excesses in the neutron burst model are now clear. The burst of neutrons allows the initially large abundances of Y and Zr (dominated by ^{89}Y and ^{90}Zr) to redistribute themselves among all the isotopes up to A=97. Crucially, the neutron burst was not strong enough to produce much ^{100}Zr. At the same time, the neutron burst scours out much of the original abundance of the Mo isotopes. Upon beta decay, the large abundances of ^{95}Y, ^{95}Zr, and ^{97}Zr produce large excesses in ^{95}Mo and ^{97}Mo. The original ^{100}Mo is slightly depleted by the burst. Because no ^{100}Zr or ^{100}Nb is made, there is no resulting ^{100}Mo excess. It is important to note in this model that the original abundances of the Y and Zr isotopes dominate those of Nb and Mo.

Fig. 4 shows the final Zr isotopic pattern relative to solar. The key feature here is that ^{96}Zr is the most overproduced isotope. Certain presolar graphite grains analyzed by RIMS also show excess ^{96}Zr (7). As noted in (7), the neutron-burst isotopic patterns of the Zr isotopes other than ^{96}Zr do not match those shown in the grains; however, it is likely the exact burst pattern is sensitive to the details of the neutron exposure. The most significant fact for the present discussion is the ^{96}Zr excess.

The requirements for the success of the neutron-burst scenario are 1) matter for which the abundances of Y and Zr dominate those of Nb and Mo and 2) a neutron burst that results in an neutron exposure of ~ 0.075 mb^{-1}. Where exactly this occurs in an exploding star has yet to be determined. We have modeled the He-rich layer, as done in (5). In fact, other environments deeper in the star may be more plausible–for example, matter that had not completed carbon burning when the supernova shock passed through it. Detailed stellar evolution models will eventually resolve this question. For now the exciting result seems to be that the SiC X grains may have formed in the same material that gave rise to the Xe-H bearing component of the presolar microdiamonds.

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References. (1) Pellin, M. J. et al. (1999) *LPSC 30*, abstract 1969. (2) Heymann, D. and Dzickaniec, M. (1979) *Proc. Lunar Planet. Sci. Conf.*, 10, 1943-1959. (3) Heymann, D. and Dzickaniec, M. (1980) *Proc. Lunar Planet. Sci. Conf.*, 11, 1179-1213. (4) Heymann, D. (1983) *Astrophys. J.* 267, 747-756. (5) Howard, W. M. et al. (1992) *Meteoritics*, 27, 404-412. (6) Meyer, B. S. (1995) *Astrophys. J. Lett.* 449, 55-58. (7) Nicolussi G. et al. (1998) *Astrophys. J.*, 504, 492-499.