NEUTRON BURST PRODUCTION OF ^{60}Fe NECESSARILY IMPLIES PRODUCTION OF ^{182}Hf. B. S. Meyer[1] and D. C. Adams[2], [1]Department of Physics and Astronomy, Clemson University, Clemson, South Carolina, 29634-0978, USA, mbradle@clemson.edu, [2]Department of Physics and Astronomy, Clemson University, Clemson, South Carolina, 29634-0978, USA, dcadams@clemson.edu.

Introduction: A plausible explanation for the origin of the abundance of live ^{26}Al and ^{60}Fe in the early solar system is injection into the proto-solar cloud [1] or disk [2] from a nearby supernova exploding no more than a few million years before condensation of the primitive solar system minerals. New models of this scenario can also explain the abundance of live ^{129}I and ^{182}Hf (e.g., [3]). In these latter models the ^{60}Fe, ^{129}I, and ^{182}Hf nuclei injected into the proto-solar cloud or disk are primarily synthesized in a neutron burst that occurs when the supernova shock wave passes through the inner part of the helium-burning shell in the star [4]. The shock heats the helium-rich material to temperatures near $T_9 = T/10^9$ K = 0.5—10 at a density of about 2 x 10^3 g/cm^3, which drives the ^{22}Ne(α,n)^{25}Mg reaction. The neutrons thus released achieve a density of about 10^{17}—10^{19} per cm^3, which is intermediate between the typical s- and r-process neutron densities. Such densities allow the neutron capture flow to branch radioactive ^{59}Fe and ^{181}Hf effectively and produce ^{60}Fe and ^{182}Hf.

While the bulk of the ^{60}Fe in the solar cloud is generally conceded to have come from a nearby supernova, ^{182}Hf can also be produced in the r-process, and the level of ^{182}Hf present in the early solar system is in line with expectations from Galactic nucleosytheis (e.g., [5]). The underabundance of ^{129}I, another r-process isotope in the early solar system, however, argues that either 1) there are multiple r-processes[6]—one responsible for most of the ^{129}I and one responsible for most of the ^{182}Hf—or 2) the bulk of the ^{182}Hf present in the early solar system was not from r-process production. We demonstrate that neutron-burst production of ^{182}Hf necessarily accompanies that of ^{60}Fe. We further demonstrate that, while neutron-burst production of ^{60}Fe can vary by several orders of magnitude depending on the peak post-shock temperature and density, the production of ^{182}Hf is fairly independent of variations in those conditions.

The Calculations: We used the Clemson University nuclear network code [7] to compute a series of neutron bursts and studied the resulting nucleosynthesis. The initial composition was drawn from a typical inner helium-shell composition in a presupernova star evolved at Clemson [3]. We followed the nuclear burning in thermodynamic trajectories that modeled post-shock evolution of stellar shells—in particular, we took the density ρ and temperature T_9 to fall exponentially from their initial post-shock values ρ_0 and $T_{9,0}$ with time according to standard prescriptions: $\rho(t) = \rho_0 \exp(-t/\tau)$ and $T_9 = T_{9,0}\exp(-t/(3\tau))$. We took the e-folding time τ to be 1 second, a value typical for the helium-burning shell. The network was complete and used species from hydrogen to bismuth.

For the calculations presented here, we considered an initial density $\rho_0 = 2\times10^3\, g/cm^3$ and an initial temperature ranging from $T_{9,0} = 0.5 - 1.0$. The calculations were cut off at one year of simulation time, by which point all neutron-rich progenitors of ^{60}Fe, ^{129}I, and ^{182}Hf had decayed to these radioactive daughters. Figure 1 shows the mass fraction X of ^{60}Fe, ^{129}I, and ^{182}Hf one year after the neutron burst relative to their initial mass fractions X_0 at the beginning of the calculation as a function of the peak temperature. All calcalculations had a peak density of 2.0 x 10^3 g/cm^3. Notice that there was some of each of these species present at the time of the supernova due to pre-explosion s-processing.

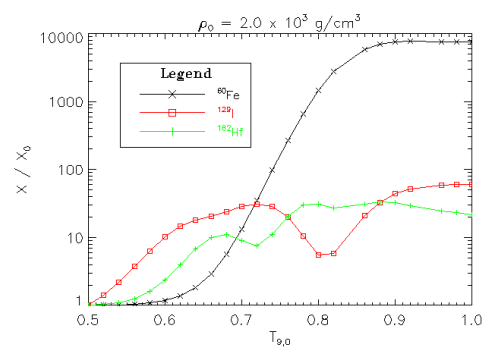

Figure 1

Discussion: It is apparent from these figures that helium-shell material shocked to temperatures above T_9 roughly 0.6 will have production of ^{60}Fe and ^{182}Hf, as well as ^{129}I. What is also striking, however, is that the enhancement of the mass fraction over the initial value for ^{129}I and ^{182}Hf is roughly uniform at X/X_0 = 10—50, once those isotopes are produced, while the production of ^{60}Fe grows by several orders of magnitude. The reason for this difference lies in the abundance of the seed nuclei available and in the relevant neutron-capture cross sections.

The dominant seed for ^{60}Fe is ^{56}Fe, which has a mass fraction of 1.1 x 10^{-3}. By contrast, the initial mass fraction of ^{60}Fe is 8.35 x 10^{-8}. The neutron-capture cross sections for Fe isotopes under the neutron-burst conditions range from roughly 10-30 millibarns. The high seed abundance and low cross sections mean that significant production of ^{60}Fe can occur as ^{56}Fe nuclei capture neutrons and move to ^{60}Fe, potentially enhancing the mass fraction of ^{60}Fe by as much as a factor of ~10^4. However, the low cross sections mean that the peak temperature must be fairly high to cause such a high production.

By contrast, the mass fraction of Hf isotopes other than ^{182}Hf at the beginning of the calculations is 8.5 x 10^{-10} while that of ^{182}Hf is 1.83 x 10^{-11}. If the neutron burst caused all Hf nuclei to capture neutrons and become ^{182}Hf, we could expect a final mass fraction of about 8.5 x 10^{-10} and an enhancement of roughly 65. The typical neutron capture cross sections range from roughly 100—200 millibarns, so the neutron flux required to allow the stable Hf seed nuclei to capture neutrons and reach ^{182}Hf is considerably less than that required for the stable Fe isotopes to reach ^{60}Fe.

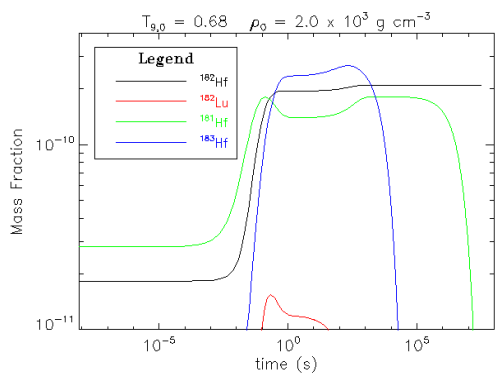

Figure 2

Figure 2 shows the time evolution of several isotopes of Hf during a neutron burst with $T_{9,0}$ = 0.68 and an initial peak density of 2.0 x 10^3 g/cm^3. As is apparent, as the neutron burst progresses, the neutron flow moves through ^{181}Hf, then to ^{182}Hf, and even on to ^{183}Hf. The final enhancement of ^{182}Hf is somewhat more than a factor of 10, roughly in line with our expectations. The low abundance of ^{182}Lu shows that there is little contribution to ^{182}Hf from lower-charge isobars.

If the peak temperature is higher, the neutron flux during the burst is greater. Figure 3 shows the time evolution of several isotopes of Hf during a neutron burst with $T_{9,0}$ = 0.86 and an initial peak density of 2.0 x 10^3 g/cm^3. For such a high temperature, the resulting high neutron flux causes the Hf isotopes to capture beyond ^{182}Hf. The final ^{182}Hf comes from lower-charge isobars produced during the flow that then decay to ^{182}Hf in the ensuing year. Since the initial abundances of Er, Tm, Yb, and Lu seeds are comparable to those of Hf, the final yield of ^{182}Hf is comparable in this case to that in the lower temperature burst. Thus, the yield of ^{182}Hf is fairly flat as a function of peak temperature, as long as it is high enough to cause a burst. A similar result holds for ^{129}I. By contrast, increasing the peak T_9 from 0.5 to 1.0 dramatically increases the ^{60}Fe yield because more of the initial ^{56}Fe moves into ^{60}Fe.

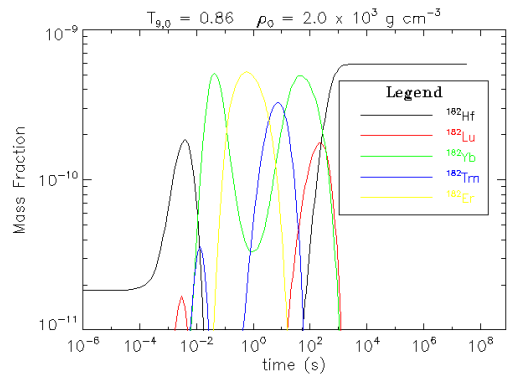

Figure 3

Results of the Calculations: The detailed results of these calculations are in FITS format. The interested user may download the files and instructions for viewing them.

Conclusions: **1)** A neutron burst that produces ^{60}Fe necessarily produces ^{129}I and ^{182}Hf. This is because the cross sections of the I and Hf isotopes are greater than those of the Fe isotopes. 2) The yield of ^{60}Fe in a neutron burst can vary greatly depending on the post-shock temperature and density. This is due to the large seed nucleus abundance and the small cross sections for the Fe isotopes. By contrast, the neutron burst yields of ^{129}I and ^{182}Hf are fairly uniform as long as the burst occurs. This means that the neutron burst yields of ^{129}I and ^{182}Hf are less sensitive to uncertainties in the pre-supernova and explosion models than the yield of ^{60}Fe.

References: [1] Cameron A. G. W. and Truran J. W. (1977) *Icarus, 30,* 447-461. [2] Ouellette N. and Desch S. J. (2004) *LPS XXXV,* Abstract #2116. [3] Meyer B. S. (2005) *ASPC, 341,* 515-526. [4] Meyer B. S. et al. (2004) *LPS XXXV,* Abstract #1908. [5] Meyer B. S. and Clayton D. D. (2000) *Sp. Sci. Rev., 92*, 133-152. [6] Wasserburg, G. J. (1996) *ApJ, 466,* L109-L113. [7] Jordan G. C., IV and Meyer B. S. (2004) *ApJ, 617,* L131-134.