INJECTION OF ^{182}Hf INTO THE EARLY SOLAR NEBULA.

B. S. Meyer, D. D. Clayton, and L.-S. The[1] and M. F. El Eid[2], [1]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978 (mbradle@clemson.edu), [2]Department of Physics, American University of Beirut, Beirut, Lebanon.

Introduction: One of the major goals of cosmoshemistry is to reconcile the inferred abundances of the roughly ten well-established extinct radioactivities with appropriate models of Galactic chemical evolution and Solar-System formation. It is certainly expected that short-lived species were present in the early Solar System due to ongoing Galactic nucleosynthesis. The difficulty is that the abundances inferred from the meteorites do not match those expectations. For example, the meteoritic abundance of ^{26}Al is ~10^4 times higher and the abundance of ^{129}I is ~10^2 times lower than the values expected from ongoing nucleosynthesis, while ^{53}Mn is in line with those expectations [1].

Meyer and Clayton [1] developed a general picture based on these notions for the ten short-lived radioactivities ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{107}Pd, ^{146}Sm, ^{182}Hf, and ^{244}Pu. In that picture, ^{53}Mn and ^{146}Sm are understood as (at least in significant measure) products of Type Ia supernovae, which maintain a steady supply of these isotopes. The low abundance of the r-process products ^{107}Pd, ^{129}I, and ^{244}Pu is due to the separation time between the last r-process event contributing to the solar system and the birth of the Sun. The high abundance of ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe relative to expectations from ongoing Galactic nucleosynthesis is due to additional formation of this isotope shortly before meteorite formation, either by injection from a nearby supernova or AGB star that tiggered collapse of the solar cloud or by irradiations from energetic particles from the early Sun. Meyer and Clayton favored injection of the last four isotopes from the outer layers of an exploding massive star. ^{182}Hf was the difficult isotope to reconcile in this picture because, although an r-process species, its abundance is in agreement with a steady-state supply in the interstellar medium. Injection along with ^{26}Al and ^{41}Ca was proposed to account for its relatively high abundance.

Injection from a Massive Star: New stellar models are now becoming available to study the possibility of injecting ^{182}Hf into the early solar cloud (e. g., [2]). We have used the output from such a model to understand the injection of ^{182}Hf. In particular, the yields from a model of an explosion of an initially 25 solar mass star (kindly provided by S. E. Woosley) were analyzed in a fashion similar to that in [1]. In particular, Figure 1 shows the result of injecting portions of the model that lie exterior to the mass cut (abscissa) into a one solar mass proto-solar cloud. For each choice of mass cut, we imagine enough stellar material is injected to explain ^{26}Al at its canonical value of ^{26}Al/^{27}Al $\approx 5 \times 10^{-5}$. Typically this requires ~10^{-4} of the total ejecta. Shown are the abundances of the short-lived radioactivities ^{26}Al, ^{41}Ca, ^{60}Fe, ^{107}Pd, ^{129}I, and ^{182}Hf that would be injected relative to their inferred abundances at the time of meteorite formation. The abundances for the short-lived species were taken from [3]. A decay interval of 0.9 Myr was taken to account for the travel time from the supernova to and incorporation into the solar cloud.

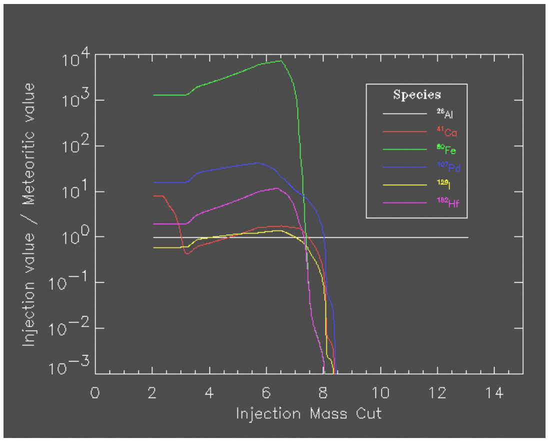

Figure 1

As is evident, injecting matter exterior to ~7 solar masses is able to account for all of these species in the early solar nebula. Meyer and Clayton, motivated by Cameron and collaborators [4], discussed possible reasons for the existence of an injection mass cut (at 7 solar masses): 1) only the mass outside 7 solar masses escape fall back into a black hole or 2) Rayleigh-Taylor fingers formed at the cloud-supernova shocked matter interface reached down only to the injection mass cut an drew this matter into the solar cloud. Alternatively, the isotopes may have been implanted into dust grains formed further inside the supernova and then shot into the solar cloud. These issues will need further investigation.

Discussion: A recent paper has shown that hibonite grains that apparently had live ^{10}Be (presumably produced by particle irradiations) do not show evidence for having had live ^{41}Ca [5]. This suggests that ^{41}Ca was injected from a massive star. Figure 1 then strongly suggests that such an injection also necessarily provided the early solar nebula with the observed ^{182}Hf abundance, as well as that of ^{26}Al, ^{36}Cl (not shown in Figure 1 but in agreement—see [1]), ^{60}Fe, ^{107}Pd, and ^{129}I. No ^{53}Mn, ^{146}Sm, or ^{244}Pu would have been injected because they come from deeper inside the star. Only if the injection is immediate, when the ^{41}Ca abundance is much higher than at 0.9 Myr as in Figure 1, does it appear possible to inject ^{41}Ca without injecting an appropriate amount of ^{182}Hf. If this happened, however, the amount of ^{41}Ca injected would be too high relative to ^{26}Al.

The injected amounts of ^{60}Fe and ^{107}Pd are perhaps too high to also accommodate the ^{41}Ca and ^{182}Hf, but nuclear physics issues may come into play here. The nuclear isomer in ^{107}Pd needs particular attention since it will affect the ^{107}Pd beta decay during stellar evolution and the explosion. We are addressing this point with the tools we developed for ^{26}Al [6]. As for ^{60}Fe, we are investigating the dependence of its yield on the neutron-capture cross section and beta-decay rate of ^{59}Fe. We are also investigating the role of the initial metallicity on the abundances, though this should produce no more than a factor of two effect.

Finally, it should be clear that the picture developed here does not require that the r process be responsible for the bulk of the live ^{107}Pd, ^{129}I, and ^{182}Hf in the early solar nebula. If true, this would obviate the need for two distinct types of r processes (one producing ^{129}I and one producing ^{182}Hf), though it would not preclude such a scenario.

References: [1] Meyer B. S. and Clayton D. D. (2000) *Space Sci. Rev.*, *92*, 133-152. [2] Rauscher T., Heger A., Hoffman R. D., and Woosley S. E. (2002) *Astrophys. J.*, *576*, 323-348. [3] Podosek F. A. and Nichols R. H. Jr. (1997) in *Astrophysical Implications of the Laboratory Study of Presolar Materials*, eds. T. J. Bernatowicz and E. K. Zinner, AIP, Woodbury, NY. [4] Cameron A. G. W., Hoflich P., Myers P. C., and Clayton D. D. (1995) *Astrophys. J.*, *447*, L53-L57. [5] Marhas K., Goswami N., and Davis A. M. (2002) *Science*, *298*, 2179-2182. [6] Gupta S. S. and Meyer B. S. (2001) *Phys. Rev. C*, *64*, 25805.