THE ^{135}Cs-^{135}Ba CHRONOMETER AND THE ORIGIN OF EXTINCT NUCLIDES IN THE SOLAR SYSTEM. S. B. Jacobsen and M. C. Ranen, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138, USA (jacobsen@neodymium.harvard.edu).

Introduction: A number of now extinct short-lived nuclides, with half-lives ranging from ~10^5 (^{41}Ca) to 10^8 years (^{146}Sm), were present in the early Solar System and provide constraints on chronometry, nucleosynthetic sources of early Solar System materials and provide a tool for identifying the environment where the Solar System formed (such as isolated star formation versus formation in a cluster of stars).

The average ratio of such a short-lived radioactive (R) isotope to a stable (S) reference isotope (N_R/N_S) in the interstellar medium (ISM) can be estimated from well established principles [1]. Also, various stellar sources have been suggested to explain the observed ratios in the early Solar System [cf. 2]. Normalizing such ratios (N_R/N_S) to the nucleosynthetic production ratio (P_R/P_S), defines the parameter $\alpha_{R/S}$ = $(N_R/N_S)/(P_R/P_S)$ which is useful in plotting such results versus the mean-life (τ) of the short-lived nuclides under consideration.

Jacobsen [3] showed that the data for the early Solar System yield three groups of short-lived nuclides in such a plot of logα vs. logτ as shown in Figure 1. The three groups are: (i) ^{53}Mn, ^{182}Hf, ^{244}Pu and ^{146}Sm lie on a trend with a slope somewhat less than 2. These nuclides are likely produced by type II supernova (SN) sources injected into the interstellar medium over the history of our galaxy, (ii) ^{129}I and ^{107}Pd are substantially below this trend and may have been produced by SN sources which appear to have been more common earlier in the history of our galaxy and (iii) ^{41}Ca, ^{26}Al and ^{60}Fe are too high to be of average galactic production; these must be a contamination from young stellar sources (dissimilar to typical SNII sources) that possibly formed within the proto-Solar molecular cloud (MC).

Thus, some nuclides (such as ^{26}Al, ^{41}Ca, ^{60}Fe) may be from contamination of the pre-solar molecular cloud by a single stellar source [supernova (SN), TP-AGB star or W-R star] close to the time of Solar System origin. Other nuclides (such as ^{146}Sm, ^{244}Pu, ^{182}Hf and ^{129}I) may primarily be related to the average composition of the ISM at the origin of the Solar System. Here we add new constraints using the ^{135}Cs-^{135}Ba chronometer based on new high precision Ba isotopic measurements.

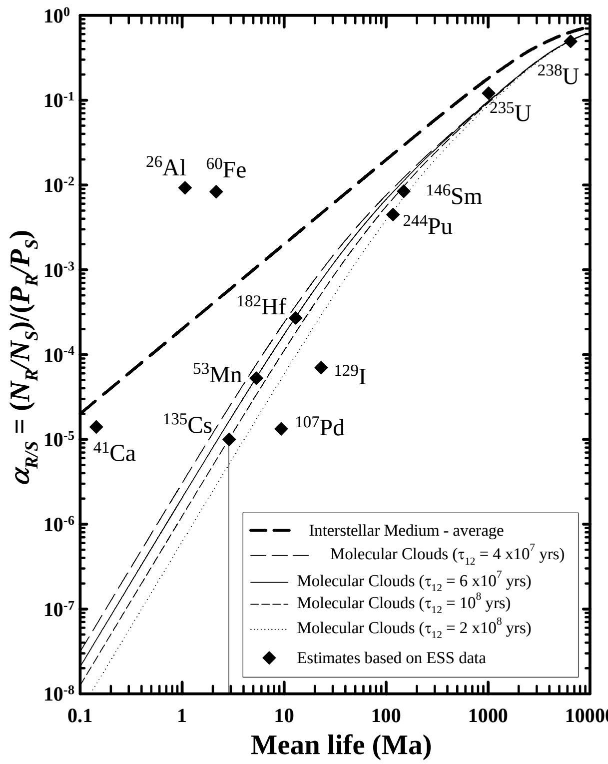

Figure 1. Comparison of ^{135}Cs (upper limit) to other early solar system short-lived nuclides after [3].

Results: As shown in Figure 2 we can now measure ^{135}Ba/^{136}Ba (when normalized to ^{134}Ba/^{136}Ba – both are s-process only isotopes) with an external reproducibility of about 10 ppm.

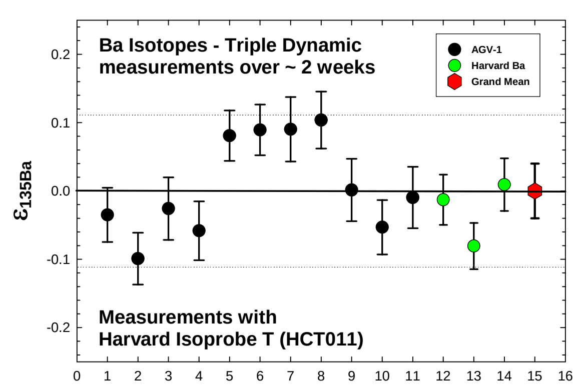

Figure 2. Reproducibility of ^{135}Ba/^{136}Ba.

Results for two carbonaceous chondrites (Murchison and Allende) and an ordinary chondrite (Bruderheim) are shown in Figure 3. The data does not establish the presence of ^{135}Cs in the early Solar System, but yields an upper limit of $^{135}Cs/^{133}Cs < 10^{-5}$ consistent with an upper limit based on CAIs [4, 5]. These results are inconsistent with the higher values (6×10^{-5} to 5×10^{-4}) based on leaching experiments of chondrites [6, 7]. A similarly high value has been hinted based on the C1 FUN inclusion [8].

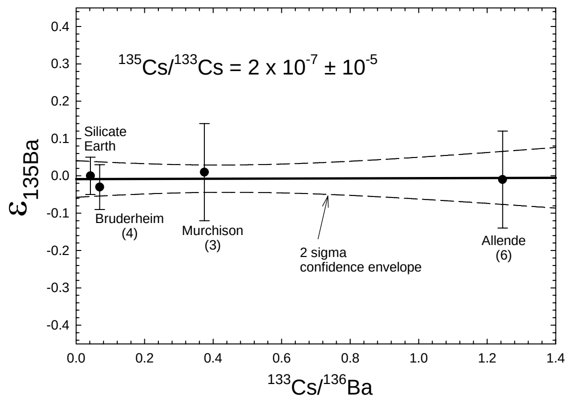

Figure 3. ^{135}Cs-^{135}Ba fossil isochron relationship for bulk chondrites and indicating numer of repeat measurements.

Discussion and Conclusions: For the ISM the parameter $\alpha_{R/S}$ has a simple relationship to the mean life, τ_R, of R: $\log\alpha_{R/S} = \log\tau_R - \log T^*$ where $T^* = T\langle\psi\rangle/\psi(T)$, $\langle\psi\rangle$ is the mean nucleosynthetic production rate, T is the duration of nucleosynthesis, $\psi(T)$ is the final production rate and $\psi(t)$ is the time dependent mass production rate from stellar sources injected into the ISM [1]. Thus, the average ISM values of the short-lived nuclides should lie on a line (the heavy dashed line in Figure 1) with a slope of 1 in a $\log\alpha_{R/S}$ vs. $\log\tau_R$ diagram in Figure 1. As shown, only ^{41}Ca is close to this line and most other points fall substantially below and close to a line with a slope of 2 which cannot be explained by the traditional free decay interval. Therefore a new two-reservoir model was proposed [3] where molecular clouds exchange matter with the remaining ISM. The isolation of material in MCs results in additional decay and can be used to evaluate the short-lived nuclide pattern in terms of the residence time of matter in molecular clouds [3], for which we have the following relationship: $\log\alpha_{R/S} = 2\log\tau_R - \log[(1 - x_{S1})\tau_{12} + \tau_R] - \log T^*$ where τ_{12} is the residence time of matter in MCs and x_{S1} is the mass fraction of matter in MCs (~0.2). For $\tau_{12} >> \tau_R$, $\log[0.8\tau_{12} + \tau_R]$ is approximately constant and in this case the slope will be close to 2 for a MC. The data that follow the ~ slope 2 line in Figure 1 are consistent with a residence time of matter in MCs of τ_{12} ~6×10^7 yrs. Thus, the pattern of short-lived nuclides is consistent with the birth of the Solar System in a MC complex that was exchanging matter with (1) the remaining ISM at a timescale of ~6×10^7 yrs and (2) with addition of fresh nucleosynthetic matter from a young star in this region at the time of Solar System formation. Thus, some nuclides (such as ^{26}Al, ^{41}Ca, ^{60}Fe) may be from contamination of the pre-solar molecular cloud by a single stellar source such as a supernova which is likely within a million years of Solar System origin if the Sun formed within a cluster of stars. However, contamination of the early Solar System by one or more massive star supernovae as the source of the shorter-lived radionuclides would likely lead to overproduction of ^{135}Cs compared to the meteoritic abundances [see also 9] as well as for other nuclides (such as ^{182}Hf) that also appear to primarily reflect the average composition of the MC where the Solar System was born. The SN contamination model overproduces ^{135}Cs by several orders of magnitude if it was a typical SNII that give rise to the galactic average evolution as modified by the molecular cloud environment. This probably does not disprove the SN contamination model, but requires some special mechanism to explain the very high ^{26}Al and ^{60}Fe seen in the early Solar System compared to ^{135}Cs. There are two likely mechanisms to explaine the very enhanced ^{26}Al addition due to the early Solar System by such a supernova. First, ^{26}Al may be enhanced due to differential injection of pre-supernova winds and supernova ejecta into the early Solar System and the early winds may also be enriched in ^{26}Al. Second, post-explosion fall-back of deep nucleosynthesis products into a neutron star or black hole may be responsible for the deficiency of other extinct radionuclides in comparison with ^{26}Al [9]. Whatever the explanation, it could not be efficient in limiting the injection into the ISM for SNIIs that inject most of the short-lived radioactive nuclides into the ISM over the history of our galaxy.

References: [1] Schramm D. N. and Wasserburg G. J. (1970) *ApJ.* 162:57–69. [2] Wasserburg G. J. et al. (2005) *Nuclear Physics A*, in press. [3] Jacobsen S. B. 2005. *ASP Conference Series* 341, 548-557. [4] Harper C. L. et al. (1992) *Meteoritics*, 27, 230. [5] Harper C. L. (1993) *J. Phys. G.*, 19, S81. [6] Hidaka et al. (2001) *EPSL* 193, 459-466. [7] Hidaka H. et al. (2003) *EPSL* 214, 455-466. [8] McCulloch, M.T. and Wasserburg, G.J. (1978) *Astrp. J*, 220 L15-L19. [9] Harper C. L. (1996) *ApJ*, 466, 1026-1038.