^{84}SR ANOMALIES IN BULK-ROCK METEORITES AND ACID-LEACHATES OF THE IVUNA CI CHONDRITE.

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Introduction: Nucleosynthetic anomalies have now been documented between meteorite reservoirs for a number of nuclides (e.g., ^{54}Cr, ^{62}Ni, ^{50}Ti, ^{92}Mo, ^{26}Al; [1-5]), with a positive correlation observed between several of these anomalies. These correlations were most likely caused by one of two contrasting processes. First, the material transporting these anomalies may not have completely mixed into the protoplanetary disk prior to solar system formation. Or alternatively, the material may have been physically well mixed without destroying the unique composition of individual grains, then subsequently unmixed by a process that discriminated between grains containing anomalies and "normal" solar grains (e.g. thermal processing; [3]). Resolving which of these two processes is most likely to have generated the observed nucleosynthetic heterogeneity is thus an important first step in deciphering the information that these anomalies preserve.

Strontium has four isotopes, of which three are relatively abundant (^{86}Sr = 9.86%, ^{87}Sr = 7.00%, ^{88}Sr = 82.58%), and are produced in differing ratios by the s- and r-processes. These processes both involve neutron addition in combination with $ß^{-}$ decay, and thus produce isotopes that fall on the neutron-rich side of the valley of stability. In contrast, the lightest isotope of strontium is produced by the p-process and is—like other isotopes falling on the neutron-poor side of the valley of stability—comparatively scarce (^{84}Sr = 0.56%).

Although s- and r-process nuclides can be formed in common stellar environments (i.e., Asymptotic Giant Branch Stars and Type-II Supernovae; [6]), the proton-rich nuclides produced by the p-process require extreme conditions that can facilitate either proton-capture or photodisintegration [6]. Although these processes are not well understood, the most plausible stellar environment for the production of p-process nuclides such as ^{84}Sr is within a Type-Ia Supernova [7].

Samples and Analytical Methods: For bulk-rock meteorite samples (and refractory Ca-Al-rich inclusions; CAIs) 20 to 50 mg of rock was crushed in an agate mortar and pestle, then dissolved in a mixture of concentrated HF and HNO_3 in a Parr bomb at 210°C for three days. Strontium was separated from the sample using a single pass over 200 µL of Eichrom Sr-Spec resin.

For the acid-leaching test, ~3 grams of the Ivuna CI chondrite was crushed using an agate mortar and pestle, then sequentially leached in increasingly aggressive acids in a sequence comparable to [1]. Each leachate was purified using a double-pass over columns containing 200 µL of Eichrom Sr-Spec resin.

Strontium isotopes were measured by thermal ionisation mass spectrometry (TIMS) using the Thermo Triton at the Center for Star and Planet Formation, University of Copenhagen. For each measurement approximately 500 ng of Sr was loaded onto a single rhenium filament in a combination of HCl, H_3PO_4, and TaF. Filaments were measured at ~22 V ^{88}Sr (equating to ~0.15 V ^{84}Sr), with all isotopes measured in Faraday cups coupled to 10^{11} Ω amplifiers. Mass bias was corrected using an ^{88}Sr/^{86}Sr ratio of 8.375209, and all anomalies are quoted relative to the SRM 987 reference standard in µ notation (i.e., parts per million). Using analyses of our terrestrial reference standards we estimate the external reproducibility of our ^{84}Sr data as ± 28 ppm (2 s.d.).

Results and Discussion: Of the samples dissolved in bulk, the two CAIs exhibit the largest anomalies in ^{84}Sr of +120 and +122 ppm, well beyond the analytical uncertainty of the method, and in excellent agreement with results published elsewhere [8,9]. NWA 2976 (ungrouped achondrite) also exhibits a positive anomaly of +42 ppm, again in excellent agreement with the results of [8]. Ivuna (CI chondrite), the only carbonaceous chondrite measured in this study, has a positive μ^{84}Sr of +11 ppm. Although this is not resolvable from earth at the precision of our method, it is within uncertainty of a previously published range for carbonaceous chondrites of +54 ± 25 ppm [8]. The remainder of the bulk meteorites sampled (angrites, eucrite, ureilite, ordinary chondrite, enstatite chondrite) range in μ^{84}Sr from –11 to +10 ppm, and are unresolvable from Earth at the resolution of our method. Again, these results are in good agreement with previously published work [8,9].

The μ^{84}Sr values of the three terrestrial rock standards analysed in this study are negative relative to the SRM 987 reference standard, with an average value of –25 ppm. This observation is in agreement with previously published data [8], and suggests that SRM 987 may be fractionated relative to Earth.

Interestingly, we observe that μ^{84}Sr values exhibit a positive correlation with previously published ^{54}Cr, ^{50}Ti, and ^{26}Al anomalies (which also exhibit positive correlations with each other) for the same meteorite classes (Figure 1; [1,3,5]).

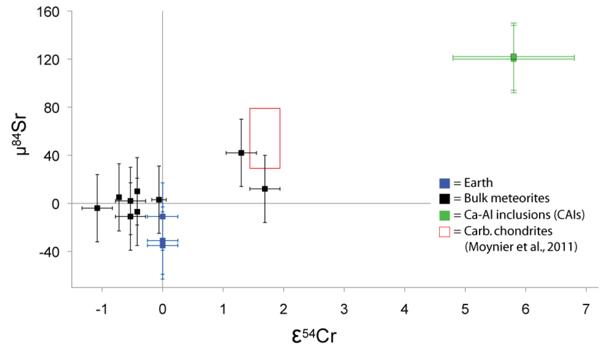

Figure 1 Plot of μ^{84}Sr versus ε^{54}Cr (from [1] and [5]) showing an example of the positive correlation observed between ^{84}Sr anomalies and several other nuclides known to be heterogeneously distributed in solar system reservoirs.

Given the correlations observed between meteorite reservoirs, one might expect to see similar patterns in the step-leaching results of different nuclides. A previously published [1] step-leaching test of several carbonaceous chondrites observed moderate negative anomalies in ^{54}Cr for weaker acid steps, followed by extreme positive anomalies in the first leach employing hydrofluoric acid, interpreted to represent a silicate carrier containing positively anomalous ^{54}Cr. In contrast, we observe moderately positive (i.e., CAI-like in magnitude) ^{84}Sr anomalies in the early phases of step-leaching (Figure 2), followed by a trend to increasingly negative μ^{84}Sr values, including two extremely negative aliquots. This pattern is not in keeping with a carrier of positively anomalous ^{84}Sr, but instead with one depleted in ^{84}Sr. Given that the two extremely negative aliquots contain some of the lowest quantities of leached strontium (<0.6% of the total sample) we suggest that presolar SiC, which is notoriously difficult to dissolve in acid, might be the carrier. Strontium isotope compositions of individual presolar SiC have been found to be depleted in ^{84}Sr by as much as 80% [10], and could thus have produced strong negative ^{84}Sr anomalies in the smallest leachates, even if only minute amounts were dissolved.

If this interpretation is correct, it rules out incomplete homogenisation as the source of correlated heterogeneities, while lending strong support to the theory that an unmixing process (such as thermal processing) could have produced the observed positive correlations from material that was physically well mixed.

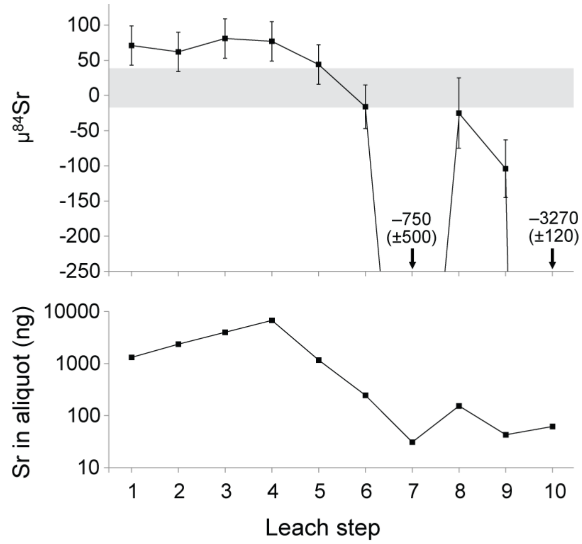

Figure 2 Measured μ^{84}Sr (top) for each aliquot of a 10-step sequential leach of the Ivuna CI chondrite, together with a log plot of the Sr concentration in ng (bottom) of each leachate. Grey band indicates measured bulk-rock composition.

In contrast to the carriers of positive ^{54}Cr, ^{50}Ti, and ^{26}Al anomalies, the observed correlation is best explained by a carrier of negatively anomalous ^{84}Sr (SiC) that behaved oppositely to other carriers (silicates?) during the unmixing process. Thus, in the case of thermal processing, the SiC would not readily sublime, and would thus remain entirely in a solid state, while the relatively volatile presolar silicates would be concentrated into the gas phase.

Importantly, this means that the source of nucleosynthetically anomalous ^{84}Sr need not be related to the sources of other heterogeneously distributed nuclides (e.g., ^{54}Cr, ^{50}Ti, ^{26}Al), and cannot be used to place constraints on the nature of the stellar source(s) that brought ^{26}Al and other nuclides of interest to the protoplanetary disk.

References: [1] Trinquier A. et al (2007) *ApJ, 655*, 1179-1185. [2] Regelous M. et al. (2008), *EPSL, 272*, 330-338. [3] Trinquier A. et al (2009) *Science, 324*, 374-376. [4] Burkhardt C. et al. (2011), *LPSC*, 2554. [5] Larsen K. et al (2011), *ApJ, 735*, L37. [6] B. S. Meyer (1994), *Annu Rev Astron Astr, 32*, 153-190. [7] Travaglio C. et al (2011), *Arxiv preprint*, arXiv:1106.0582. [8] Moynier F. et al. (2011), *LPSC*, 1239. [9] Hans U. et al. (2011), *LPSC*, 2672. [10] Nicolussi G. et al. (1998), *Phys Rev Lett, 81*, 3583-3586.