

STRONTIUM STABLE ISOTOPE COMPOSITION OF ALLENDE FINE-GRAINED INCLUSIONS

B. L. A. Charlier¹, F. L. H. Tissot² and N. Dauphas³. ¹SGEES, Victoria University of Wellington, Kelburn Parade, Wellington 6140, New Zealand (bruce.charlier@vuw.ac.nz), ²Dept. of Earth, Atmospheric and Planetary Sciences, MIT, 77 Massachusetts Avenue, 54-1118 Cambridge, MA 02139, USA, ³Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago.

Introduction: Isotopic anomalies are departures from the laws of mass-dependent fractionation that cannot be explained by radioactive decay, cosmogenic effects, or exotic isotopic fractionation processes such as nuclear field shift or magnetic effects [1 and references therein]. These anomalies often have a nucleosynthetic origin and provide clues on the stellar origin and solar system processing of presolar dust. Anomalies are most often found in refractory elements of relatively low mass, so Sr is a prime target for study. The four stable isotopes of strontium are useful for discerning the various nucleosynthetic origins of early solar system building blocks and the timing of accretion processes. Strontium-84 is the least abundant (0.56%) of these isotopes, but is particularly significant in being a *p*-process only nuclide that is produced in core-collapse or type Ia supernovae [2,3]. The more abundant isotopes ⁸⁶Sr (9.86%), ⁸⁷Sr (7.00%) and ⁸⁸Sr (82.58%) are produced in *s*- and *r*-processes in asymptotic giant branch stars and other stellar types [4]. Additionally, ⁸⁷Sr is produced by ⁸⁷Rb decay in proportions that dominate over possible nucleosynthetic variations but provide timings of early solar system processes, most notably volatile element depletion [5-7]. Furthermore, variations in strontium isotopic ratios caused by high-temperature mass-dependent fractionation [8] are also important [9-12], as they provide insights into nebular and accretionary processes.

Studies of stable Sr variations have thus far been limited to three approaches. Firstly, the classical approach is correction of instrumental mass fractionation by internal normalization to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Taken at face value, such data indicate potential small positive ⁸⁴Sr anomalies in bulk carbonaceous chondrites [13], but information about natural stable isotope fractionation is lost. Second, those that resolve fractionation in one of the isotope pairs – usually ⁸⁶Sr/⁸⁸Sr – using fractionation correction to an external element [11,12]. Thirdly, double-spike methodologies that resolve all the isotope ratios without recourse to internal or external normalisation, providing true relative isotopic compositions [9,10]. In the case of the latter examples, this early work was limited to a precision of ~0.25 and ~0.5 % for the ⁸⁸Sr/⁸⁶Sr and ⁸⁴Sr/⁸⁶Sr ratios respectively and only broad trends in mass-dependent fractionation could be

determined. Measurements of ⁸⁴Sr/⁸⁶Sr ratios were well below the necessary precision to reveal any non mass-dependent anomalies in the ⁸⁴Sr abundance in the separated CAIs from Allende.

Here, we present new high-precision TIMS ⁸⁴Sr/⁸⁶Sr results for a suite of previously studied fine- and coarse-grained CAIs from Allende [14] in order to investigate nucleosynthetic anomalies associated with variations in *p*-process ⁸⁴Sr abundances. Measurements of spiked aliquots are underway to determine the Sr stable isotopic fractionation on the same samples.

Experimental: Initial digestions were carried out for the study of [14] and an aliquot was taken for Sr isotope analysis. This aliquot was further divided into two equal portions, one of which was optimally spiked with an ⁸⁴Sr-⁸⁶Sr double spike (DS), the other left unspiked. The spike amount required for optimal spiking was based on the amount of Sr present from measurements of trace elements in separate aliquots of the same samples. Natural and DS aliquots were dealt with independently and all manipulations and separations were carried out in separate laminar flow cabinets only using beakers and columns specifically designated for use with spiked and natural samples, respectively. The number and type of manipulations for the DS and natural aliquots were identical in order to remove the possibility of differential blank issues. The spike was added to the samples prior to column separation in order to circumvent possible column-induced fractionation. Sr was separated from both aliquots using identical protocols involving sorbing the Sr onto Sr-spec resin in 8M HNO₃, followed by recovery of Sr in 0.05 M HNO₃ [15].

Measurements were carried out on the VUW Thermo-Finnigan Triton TIMS in static mode with a standard configuration using 6 Faraday collectors and 10¹¹ Ω feedback resistors. Samples were loaded on outgassed zone-refined single Re filaments with a Ta₂F₅ activator. Runs used amplifier rotation and consisted of 540 ratios, 16 sec integrations with two minute baselines measured every block. Mass fractionation was corrected by assuming $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$.

Results: Results are shown Figure 1, where ⁸⁴Sr/⁸⁶Sr ratios are reported in μ-units ($\mu^{84}\text{Sr} = 10^6$ relative deviations from average NBS-987). External reproducibility was 13.3 μ⁸⁴Sr and is denoted by the

shaded band. CAI data define a range in $\mu^{84}\text{Sr}$ values from +30.3 (within error of the standard data) to +286.5. Four terrestrial rock standards - two each of granite G3 and basalt BCR-2 - are shown for comparison and agree well with the standard data (i.e., no anomaly detectable). A compilation of previously published data for normal (i.e., non-FUN) refractory inclusions from CV3 is also plotted for comparison.

Discussion and conclusion:

FUN inclusions show large negative $\mu^{84}\text{Sr}$ anomalies that can reach ~ -5000 [16,17]. In contrast, non-FUN CAIs display positive anomalies that cluster around $\sim +120$ [7,18]. Recent measurements of other elements have suggested that non-FUN CAI could have formed from a uniform isotopic reservoir of non-terrestrial isotopic composition [18]. Our new results show that this view is correct to first order but that significant variations are present between CAIs. In particular, we report the largest $\mu^{84}\text{Sr}$ excess measured thus far in a bulk CAI of +286.5. Because this value is more anomalous than the isotopic compositions defined by other meteorites, this cannot be due to dilution by matrix or terrestrial Sr, which have near-normal compositions. Instead, it must reflect some heterogeneity in the isotopic composition of the region in which non-FUN CAIs formed.

Several scenarios exist for explaining the presence of isotopic anomalies in meteorites and their components. One is that those anomalies were simply inherited from large scale heterogeneities that existed in regions of the molecular cloud core that collapsed to form the Sun [19]. Another is that the solar system started with a more or less uniform isotopic composition and isotopic anomalies were created by thermal processing [20] or grain size sorting [21] that separated components with distinct isotopic signatures. One possible consequence of the thermal processing model is that the creation of isotopic anomalies would be accompanied by mass-dependent fractionation that is usually a characteristic of evaporation/condensation processes. Measurements are currently underway to document the mass-dependent component of the isotopic variations to search for correlations with isotopic anomalies. The large range of $\mu^{84}\text{Sr}$ variations measured among the studied CAIs makes this an ideal sample set to test this idea.

References:

[1] Dauphas N. and Schauble E. A. (2016) *Ann. Rev. Earth Planet. Sci.*, 44, 709. [2] Rauscher T. et al. (2002) *APJ*, 576, 323. [3] Travaglio C et al. (1999) *APJ*, 510, 325. [4] Nicolussi G. K. et al. (1998) *Phys. Rev. Lett.*, 81, 3583. [5] Papanastassiou D. A. et al. (1969) *EPSL*, 5, 361. [6] Halliday A. N. and Porcelli D (2001) *EPSL*, 192, 545. [7] Hans U (2013) *EPSL*, 374,

204 [8] Young E D et al. (2002) *GCA*, 66, 1095. [9] Patchett P J (1980) *Nature*, 283, 438. [10] Patchett P J (1980) *EPSL*, 50, 181. [11] Moynier F (2010) *EPSL*, 300, 359. [12] Charlier B L A et al. (2012) *EPSL*, 329, 31. [13] Moynier F et al. (2012) *APJ*, 758, 45. [14] Tissot F L H et al. (2016) *Sci. Adv.* 2. E1501400. [15] Charlier B L A et al. (2006) *Chem. Geol.*, 232, 114. [16] Papanastassiou D.A., Wasserburg G.J. (1978) *GRL* 5, 595-598. [17] Loss R. et al. (1994) *ApJ* 436, L193-L196. [18] Brennecke G.A. et al. (2013) *PNAS* 110, 17241-17246. [19] Dauphas N. et al. (2002) *ApJ* 565, 640-644. [20] Trinquier A. et al. (2009) *Science* 324, 374-376. [21] Dauphas N. et al. (2010) *ApJ* 720, 1577-1591. [22] Paton C. et al. (2013) *ApJ Lett.*, 763, L40. [23] Shollenberger Q. R. (2015) *LPSC* 46, #2593 [25].

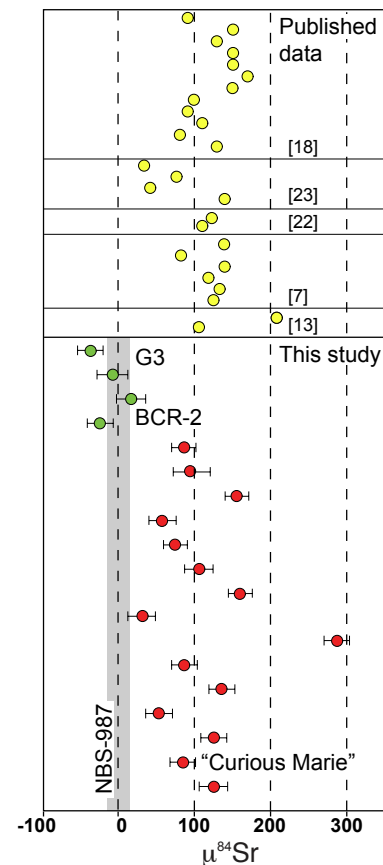


Figure 1. $\mu^{84}\text{Sr}$ compositions of 16 Allende CAIs previously studied by [14] compared to terrestrial rock standard and previously published CAI data.