

Introduction

The nucleosynthetic history of isotopes, their abundances and spatial distribution within the circumstellar disk help us identify the different stellar contributions and mixing processes active in the early the Solar System. Among the many isotopes found in nature, short-lived radioisotopes (SLRs) are essential for quantifying the temporal evolution of the early Solar System. A potentially useful short-lived isotope system that has been infrequently studied to date is ¹³⁵Cs-¹³⁵Ba ($t_{1/2} \sim 2.3$ Ma; [1]) which comprises a volatile parent nuclide and a refractory daughter nuclide and is useful for dating condensation processes and the accretion of planetary bodies. Here, refractory inclusions from Allende (CV3) and NWA753 (R3.9) were analyzed for Ba isotope variability.

Samples

- 4 Allende calcium-aluminium-rich inclusions (CAI 1,2,4,5; Fig. 1)
- 1 Allende dark inclusion (H73)
- 2 Unequilibrated type 3 fragments from NWA753 (H74, H75)

Methods

- Isolation of refractory inclusions from whole rock sample using a dental burr under optical microscope
- HF-HNO₃ digestion in sealed non-pressurized Savillex® beakers
- Isolation of Ba by column chromatography [2]
- Isotope measurements by Thermal Finnigan Triton TIMS
- Cs/Ba determination by LA-ICPMS
- Ba isotopes data are presented using the μ notation (where $x = 132, 134-137$):

$$\mu = \left\{ \frac{(^{13x}\text{Ba}/^{138}\text{Ba})_{\text{sample}}}{(^{13x}\text{Ba}/^{138}\text{Ba})_{\text{standard}}} - 1 \right\} \times 10^6$$

Results

The Ba isotope data collected from Allende CAI 1 (Type B2), CAI 2 (Type A), and CAI 5 show an excess of ¹³⁵Ba (~55 ppm) with terrestrial compositions for the remaining isotopes (Fig. 2). The remaining refractory inclusions possess terrestrial Ba isotope compositions.

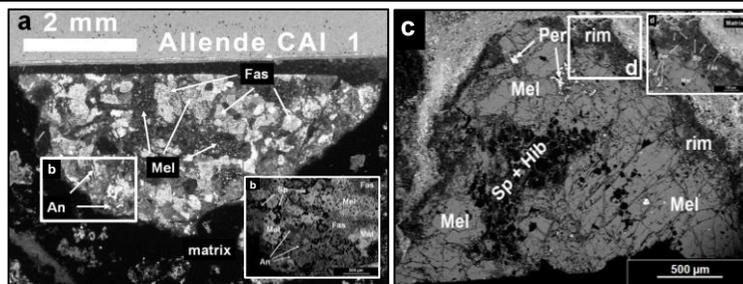


Fig. 1 Overview of (a) CAI 1 (photomicrograph, crossed polars), and (c) CAI 2 (backscatter electron image, BSE); (b) and (d) BSE images showing detail in (a) and (c).

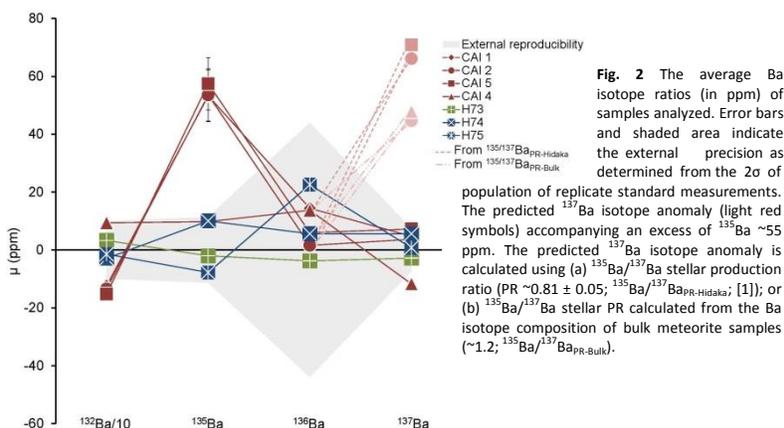


Fig. 2 The average Ba isotope ratios (in ppm) of samples analyzed. Error bars and shaded area indicate the external precision as determined from the 2 σ of population of replicate standard measurements. The predicted ¹³⁵Ba isotope anomaly (light red symbols) accompanying an excess of ¹³⁵Ba ~55 ppm. The predicted ¹³⁷Ba isotope anomaly is calculated using (a) ¹³⁵Ba/¹³⁷Ba stellar production ratio (PR ~0.81 ± 0.05; ¹³⁵Ba/¹³⁷Ba_{PR-Hidaka}; [1]); or (b) ¹³⁵Ba/¹³⁷Ba stellar PR calculated from the Ba isotope composition of bulk meteorite samples (~1.2, ¹³⁵Ba/¹³⁷Ba_{PR-Bulk}).

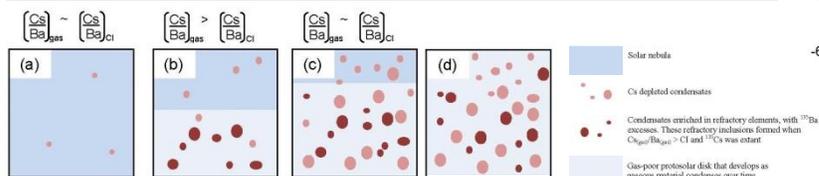


Fig. 3 A schematic describing how the presence of a superchondritic Cs/Ba reservoir, while ¹³⁵Cs was extant, enabled the accumulation of radiogenic ¹³⁵Ba to be resolved from ¹³⁵Ba_{Cs}.

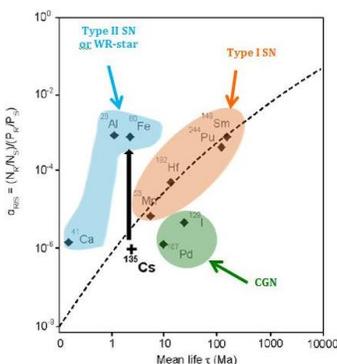
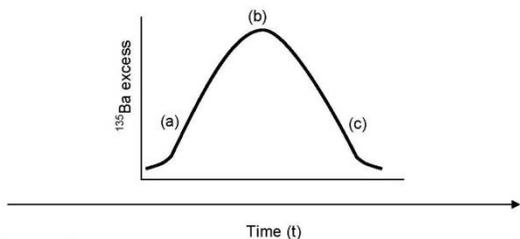


Fig. 4 The mean life times (τ in Ma) of short-lived nuclides plotted against their meteoritic abundance expressed as $\alpha_{R/S}$, where $\alpha_{R/S} = (N_R/N_S)/(P_R/P_S)$. The average ratio of a SLR (R) and a stable (S) reference isotope (N_R/N_S) is normalized to the nucleosynthetic production ratio (P_R/P_S) which defines the parameter $\alpha_{R/S}$. Figure based on [4].

Discussion

Origin of ¹³⁵Ba excess:

(1) **Neutron capture reactions:** All stable Ba isotopes have low neutron capture cross sections thus it is unlikely that secondary neutron reactions could have enriched ¹³⁵Ba alone. The development of a positive ¹³⁵Ba anomaly could potentially occur via a neutron reaction pathway from neighboring nuclides, but such a path is currently unknown.

(2) **Nucleosynthetic anomalies:** Incomplete mixing of freshly synthesized material (e.g., presolar grains and nucleosynthetic ejecta) in the solar nebula can explain coupled ¹³⁵/¹³⁷Ba excesses [1,3,4]. Estimates of the ¹³⁷Ba excess associated with a ~55 ppm ¹³⁵Ba are made using different production ratios (Fig. 2). If present, the estimated ¹³⁷Ba excess would be clearly resolvable from the external reproducibility of the standards (~10 ppm).

(3) **Radioactive decay of ¹³⁵Cs to ¹³⁵Ba:** The ¹³⁵Ba excess is interpreted here to have developed from the decay of SLR ¹³⁵Cs. This contribution is unlikely to have ¹³⁵Ba occurred via *in situ* decay of live ¹³⁵Cs because there is no correlation between ¹³⁵Ba excess and a superchondritic Cs/Ba (<0.0015, where chondritic Ca/Ba ~ 0.0795). Rather, we suggested that a transient, high Cs/Ba (> CI) reservoir existed in the early Solar System when ¹³⁵Cs was extant, and that in this setting some early condensates recorded the presence of live ¹³⁵Cs as a ¹³⁵Ba excess (Fig. 3).

Nucleosynthetic source of ¹³⁵Cs:

The nucleosynthetic source of ¹³⁵Cs can be constrained by reconciling the predicted astrophysical ¹³⁵Cs/¹³³Cs₀ abundance with its abundance in meteorites. The currently accepted value for the ¹³⁵Cs/¹³³Cs₀ ~ 4.8 ± 0.8 × 10⁻⁴ [1] of the Solar System, however, may be underestimated because live ¹³⁵Cs could have been extinct by the time the nebula had cooled enough to condense Cs_(g) (Fig. 4) If the initial meteoritic abundance of ¹³⁵Cs was indeed higher than is currently thought, it is feasible that ¹³⁵Cs was added to the Solar System along with ⁴¹Ca and ²⁶Al from contamination of the pre-solar molecular cloud by a single stellar source (e.g., a Wolf-Rayet star).

