

**THE BERYLLIUM-10 ABUNDANCE IN AN UNUSUAL HIBONITE-PEROVSKITE REFRACTORY INCLUSION FROM ALLENDE: IMPLICATIONS FOR THE ORIGIN OF  $^{10}\text{Be}$ .** M.-C. Liu<sup>1</sup> and L. P. Keller<sup>2</sup>,  
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**Introduction:** Beryllium-10 (decays to  $^{10}\text{B}$ ,  $t_{1/2} = 1.3$  Myr) is a radionuclide that exclusively requires a spallation origin. Therefore, one could obtain important insights into the irradiation environment in the solar nebula by understanding the distribution and abundance of this radionuclide in meteoritic inclusions. Most previous data are derived from B isotopic analysis of coarse-grained CV3 Ca-Al-rich Inclusions (CAIs) that have  $^{26}\text{Al}/^{27}\text{Al}$  close to the canonical level of  $5 \times 10^{-5}$ , and inferred  $^{10}\text{Be}/^9\text{Be}$  ratios between  $4 \times 10^{-4}$  and  $1 \times 10^{-3}$  [1–5].  $^{26}\text{Al}$ -depleted FUN (Fractionated and Unknown Nuclear anomalies) CAIs are less studied due to their rarity. FUN CAIs are thought to have formed prior to homogenization of  $^{26}\text{Al}/^{27}\text{Al}$  and stable isotope anomalies (e.g.,  $^{50}\text{Ti}$ ) in the solar nebula, and thus represent one of the oldest Solar System solids [6]. So far, only three FUN CAIs (Axtell 2771, KT-1 and HAL) from CV3 chondrites have been measured for  $^{10}\text{Be}$ . They are characterized by variable  $^{10}\text{Be}/^9\text{Be}$  ratios between  $(2.7\text{--}4.4) \times 10^{-4}$  [4,7]. Another group of rare,  $^{26}\text{Al}$ -free and isotopically more anomalous inclusions, namely platy hibonite crystals (PLACs) from CM2 chondrites, have well-defined  $^{10}\text{Be}/^9\text{Be} = (5.3 \pm 1.0) \times 10^{-4}$  [8].  $^{26}\text{Al}$ -free CAIs appear to have lower  $^{10}\text{Be}/^9\text{Be}$  than  $^{26}\text{Al}$ -bearing CAIs, although large analytical errors associated with some data would allow for an apparent overlap.

It has been argued that the observed  $^{10}\text{Be}$  variation resulted from the in-situ production of this radionuclide in CAIs (or their precursors) by irradiation, and the ratio difference simply reflects the fluctuation in projectile fluences [e.g., 9]. Another observation in support of this explanation comes from these CAIs' initial  $^{10}\text{B}/^{11}\text{B}$  ratios, most of which are higher than the chondritic value 0.2478 [10]. This has been interpreted as a result of mixing between spallogenic B ( $^{10}\text{B}/^{11}\text{B} = 0.4$ , co-produced with  $^{10}\text{Be}$  in the irradiated solids) and a chondritic component [5,8]. Alternatively, given that all the inferred ratios in CAIs never fall below  $3 \times 10^{-4}$ , it has been proposed that the Solar System formed with baseline  $^{10}\text{Be}/^9\text{Be}$  at this level, which originated from cosmic ray irradiation of the parental molecular cloud, and any value higher than this is a result of additional in-situ spallation [4,11]. Although not explicitly stated in this model, one would expect that inclusions that incorporated the background  $^{10}\text{Be}$  abundance should form with the chondritic B isotopic ratio. However, the three FUN CAIs all have supra-chondritic  $^{10}\text{B}/^{11}\text{B}$  indicative of the presence of a spallogenic component. To test whether some  $^{10}\text{Be}$  did come into the solar nebula by inheritance,

a better understanding of  $^{10}\text{Be}/^9\text{Be}$  and initial  $^{10}\text{B}/^{11}\text{B}$  in  $^{26}\text{Al}$ -free, isotopically anomalous samples is needed. Here we present the result of  $^{10}\text{Be}$ - $^{10}\text{B}$  system in an unusual hibonite-perovskite inclusion SHAL (son of HAL) from Allende.

**Sample and Ion Microprobe Analysis:** SHAL consists of a large ( $\sim 500 \times 200$   $\mu\text{m}$ ) single hibonite crystal and coexisting blocky perovskite ( $\sim 200$   $\mu\text{m}$  in size) [12]. The hibonite part is similar to the FUN inclusion HAL in several aspects: nearly pure hibonite stoichiometry, fractionated oxygen isotopes, very low  $^{26}\text{Al}/^{27}\text{Al}$  ( $< 3 \times 10^{-6}$ ), and the preservation of  $^{50}\text{Ti}$  enrichment (by 14%) [12, 13]. The perovskite also lacks resolvable  $^{26}\text{Mg}$  excesses (albeit larger analytical uncertainties) and shares essentially the same Ti isotopic compositions as hibonite [4]. Such isotopic compositions recorded in SHAL imply that this inclusion is also FUN and, like other FUN CAIs, possibly formed when the solar nebula was still heterogeneous.

The boron isotopic analysis was performed on the UCLA ims-1290 ion microprobe by following the procedure described in [1]. A 20nA  $^{16}\text{O}^-$  primary beam, focused into a 15  $\mu\text{m}$  spot, was generated by a Hyperion II Radio-Frequency source. Secondary ions with a mass sequence  $^6\text{Li}^+$ ,  $^7\text{Li}^+$ ,  $^9\text{Be}^+$ ,  $^{10}\text{B}^+$ ,  $^{11}\text{B}^+$  and  $^{27}\text{Al}^{++}$  were collected in peak-hopping mode. Madagascar hibonite, NBS 612 and 614 glasses were used as standards to correct for instrumental mass fractionation and the relative sensitivity factor. Isotope ratios were calculated by using total counts [14].

**Result and Discussion:** Large  $^{10}\text{B}$  excesses correlating with  $^9\text{Be}/^{11}\text{B}$  ratios were found in SHAL hibonite, implying the former presence of  $^{10}\text{Be}$  in this inclusion at the level of  $^{10}\text{Be}/^9\text{Be} = (3.06 \pm 0.63) \times 10^{-4}$  ( $2\sigma$ ,  $\chi^2 = 0.85$ ; Fig 1). This value is consistent with those found in other FUN inclusions within analytical errors, but is resolvably lower than those in CM PLACs and in other CV CAIs. The intercept of the isochron, indicating the initial  $^{10}\text{B}/^{11}\text{B} = 0.2478 \pm 0.0027$  that SHAL formed with, is essentially chondritic, whereas other FUN inclusions all have supra-chondritic initial  $^{10}\text{B}/^{11}\text{B}$ .

The Be-B isotopic composition of SHAL suggests that this inclusion may not have been irradiated, and its  $^{10}\text{Be}$  could have been inherited from the molecular cloud. If other FUN CAIs also formed in the same reservoir, their supra-chondritic initial  $^{10}\text{B}/^{11}\text{B}$  ratios would certainly demand another explanation. It is likely that Axtell 2771 and KT-1 experienced weak irradiation at a fluence sufficient to alter their initially chondritic

$^{10}\text{B}/^{11}\text{B}$  ratio to the observed levels (0.2518 and 0.2544, respectively) because of the extremely low [B] (lowest value  $\sim 0.5$  ppb; [4]), but would only result in very low  $^{10}\text{Be}/^9\text{Be} \sim (4-5) \times 10^{-5}$ . Another possibility is that the boron isotopic ratio in the solar nebula when FUN CAIs formed was heterogeneous. Although impossible to completely rule out, the lack of experimental support makes this explanation less attractive.

The  $^{10}\text{Be}$  abundance in SHAL could also be explained solely by irradiation. With the measured [Be] = 2 ppm in SHAL, a proton fluence of  $\sim 2 \times 10^{19} \text{ cm}^{-2}$  is needed to account for the observed  $^{10}\text{Be}/^9\text{Be}$  ratio. However, this fluence would significantly shift the B isotopic ratio of SHAL from chondritic to  $\sim 0.251$  (the average [B] is  $\sim 50$  ppb). The same result is true of Axtell 2771 and KT-1: when the observed  $^{10}\text{Be}/^9\text{Be}$  ratios are accounted for purely by irradiation,  $^{10}\text{B}/^{11}\text{B}$  would be higher than the reported values.

One issue that could complicate the above interpretations is the thermal processing responsible for the strong mass-dependent isotopic fractionation (e.g., oxygen) in these FUN CAIs. Boron is moderately volatile and could largely, if not completely, escape the inclusions during intense evaporation. If these FUN CAIs inherited  $^{10}\text{Be}$  from the molecular cloud material, and evaporation took place before  $^{10}\text{Be}$  had decayed significantly, the starting  $^{10}\text{B}/^{11}\text{B}$  ratio for these solids would be very sub-chondritic. So far no evidence supports the existence of such sub-chondritic initial  $^{10}\text{B}/^{11}\text{B}$  in FUN CAIs. A possible scenario for FUN inclusions to have chondritic to supra-chondritic initial  $^{10}\text{B}/^{11}\text{B}$  involves complete loss of B from their precursors followed by interactions with a chondritic B reservoir. Some of these solids were then subjected to weak irradiation as described above to raise the initial  $^{10}\text{B}/^{11}\text{B}$  ratios.

If  $^{10}\text{Be}$  in FUN inclusions was accounted for by irradiation of evaporation residues, spallation could shift sub-chondritic  $^{10}\text{B}/^{11}\text{B}$  upwards. To what extent the  $^{10}\text{B}/^{11}\text{B}$  ratio would increase depends on the initial B content the FUN precursors formed with and how much of this initial B was lost during evaporation. In the case of complete B loss, the post-irradiation solids would be characterized by a pure spallogenic  $^{10}\text{B}/^{11}\text{B}$  ratio (= 0.4). Since the observed initial  $^{10}\text{B}/^{11}\text{B}$  ratios in FUN inclusions are much lower than this, it would be required that these solids subsequently experience isotopic exchange with a chondritic B reservoir before  $^{10}\text{Be}$  had decayed significantly.

Taken at face value, the  $^{10}\text{Be}$  abundance and initial  $^{10}\text{B}/^{11}\text{B}$  ratio in SHAL would support the hypothesis that the Solar System formed with a background  $^{10}\text{Be}/^9\text{Be}$  value of  $\sim 3 \times 10^{-4}$ . However, if one takes into account the evaporation processes that these FUN inclusions have encountered, in-situ irradiation of solids appears to be a

more straightforward mechanism. The currently available dataset of  $^{10}\text{Be}$  abundances in FUN inclusions does not allow for a firm conclusion on the origin of this radionuclide. More data in such rare,  $^{26}\text{Al}$ -free CAIs will be able to shed more light on this problem.

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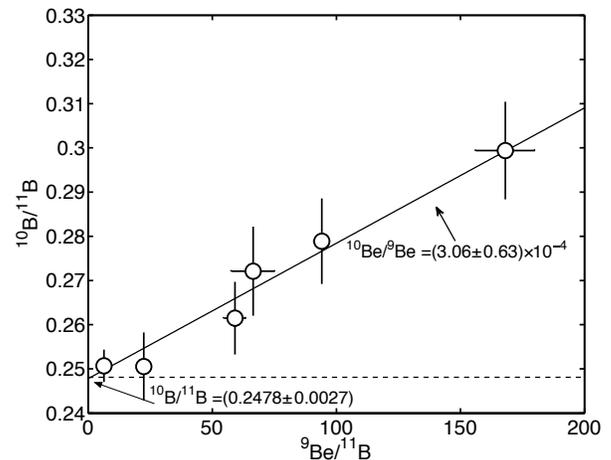


Fig 1. A  $^{10}\text{Be}$ – $^{10}\text{B}$  isochron plot for SHAL. Errors are 2 sigma.