Be-B isotope systematics in chondrules from Y82094 (ungrouped C3.2) chondrite.

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Introduction:

Beryllium-10, which decays to ^{10}B with a half-life of 1.4 Myr [1], is considered as a key indicator of irradiation processes by solar or galactic cosmic rays in the early solar system (ESS). (Note, however, that some amount of ^{10}Be can also be produced by neutrino reactions with core-collapse supernovae [2, 3].) Many of the Be-B isotopic studies have been conducted on refractory inclusions (CAIs) from CV chondrites, which tend to show the inferred initial ^{10}Be/^{9}Be ratios of (5-10) x 10^{-4} [4-7], but recent ion microprobe studies including CH/CB CAIs have revealed that the initial ^{10}Be/^{9}Be ratios in CAIs are much more variable [8, 9]. These data strongly suggest that the origin of ^{10}Be in ESS is spallation reactions induced by solar cosmic rays and the solar materials [9].

Chondrules are thought to be originated from isotopically and probably spatially distinct disk regions from CAI forming regions, because of their ^{16}O-poor *vs* ^{16}O-rich compositions, high *vs* low ambient temperatures, etc. (e.g., [10, 11]. Hence, the determination of ^{10}Be abundances in chondrules would offer a different viewpoint for the origin of ^{10}Be in the early solar system. Searching for ^{10}Be in chondrules has been attempted [12], but chondrules with high enough Be/B to resolve ^{10}B excesses appear to be extremely rare. Sugiura (2001) [12] analyzed anorthite in chondrules from the Y82094 (ungrouped C3.2) chondrite and found a possible correlation between ^{10}B excesses and Be/B ratios, but the results are not conclusive due to relatively large errors. In order to better understand the distribution of ^{10}Be in chondrules, we further conducted Be-B isotope analyses for chondrules in Y82094 chondrite using NanoSIMS.

Experimental:

We analyzed two chondrules Y94-42C2 and Y94-42C14, consisting of Mg-rich olivine (Fo_{98-99}) crystals embedded in fine-grained mesostasis or poikilitically enclosed in large euhedral low-Ca pyroxene (En_{98}) phenocrysts, minor amounts of euhedral high-Ca pyroxene ($En_{56}Wo_{43}$ with 6.7-9.2 wt % Al_2O_3, and 1.0-1.2 wt % TiO_2) in mesostasis, and Fe-Ni metal. The mesostasis shows a fine-grained texture and different phases cannot be individually measured.

Be-B isotopic measurements were performed with the NanoSIMS 50 installed at Atmosphere and Ocean Research Institute, the University of Tokyo. Using an $^{16}O^-$ primary ion beam, 2-5 nA intensity and 5-7 μm in diameter, the sample was pre-sputtered by rastering the beam over ~15 x 15 μm^2 sized areas, then analysis were made by rastering ~10 x 10 μm^2 sized areas. Only the central ~7 x 7 μm^2 sized areas were used for the analysis. Secondary ions of ^{9}Be, ^{10}B, ^{11}B, and ^{30}Si were detected simultaneously with four electron multipliers. The ^{9}Be/^{11}B relative sensitivity factor was determined from measurements of NIST 610 and 612 glasses [13]. We performed the analysis in two separate periods.

Results and Discussion: In the case of Sugiura (2001) [12], they conducted only one Be-B measurement for each chondrule because of the large (~30 μm in diameter) beam size. In this study, taking advantage of the high spatial resolution of the NanoSIMS, we successfully performed replicate analyses for different spots on single chondrules. In the first analysis period, we performed a total of 9 measurements for the chondrule Y94-42C2, and 7 measurements for another chondrule Y94-42C14. Mesostases show higher and variable ^{9}Be/^{11}B ratios of 4-10. We succeeded only one high-Ca pyroxene analysis in the mesostasis of Y94-42C2, which shows a very low ^{9}Be/^{11}B ratio of 0.03. Some analysis points in mesostases show resolvable excesses in ^{10}B (up to ~90 ‰ in Y94-42C2 and up to ~120 ‰ in Y94-42C14), which seem to correlate weakly with the ^{9}Be/^{11}B ratios. The initial $(^{10}Be/^{9}Be)_0$ ratio can be determined from the slope of the ^{10}B/^{11}B *vs* ^{9}Be/^{11}B diagram. For Y94-42C2, the initial $(^{10}Be/^{9}Be)_0$ ratio was estimated to be $(2.6 \pm 2.4) \times 10^{-3}$ (2σ error), only slightly positive with a large error, with an intercept of $(^{10}B/^{11}B)_0 = 0.245 \pm 0.015$ (2σ error), similar to the chondritic value (0.2481 [14])) within uncertainty. For Y94-42C14, due to lack of data for low Be/B phases (e.g., high-Ca pyroxene), the "isochron" was poorly determined with an initial $(^{10}Be/^{9}Be)_0$ ratio of $(1.1 \pm 3.8) \times 10^{-3}$ and an intercept of 0.253 ± 0.029 (2σ errors). The results of the first analysis period thus demonstrate a hint of the presence of live ^{10}Be at the time of the chondrule formation, though the results are still far from conclusive due to large uncertainties.

In the second analysis period, we further conducted Be-B isotope analyses on the same chondrules, and successfully measured 5 additional spots for each, including two high-Ca pyroxene phases for each. The initial $(^{10}Be/^{9}Be)_0$ ratio and the initial $(^{10}B/^{11}B)_0$ ratio are estimated to be $(0.6 \pm 1.2) \times 10^{-3}$ and 0.257 ± 0.007 (2σ errors), respectively, for Y94-42C2, and $(0.1 \pm 0.8) \times 10^{-3}$ and 0.260 ± 0.005 (2σ errors), respectively, for Y94-42C14. The inferred initial $(^{10}Be/^{9}Be)_0$ ratios are no longer resolvable from zero within uncertainties, and the initial $(^{10}B/^{11}B)_0$ ratios for both of these two chondrules are clearly positive beyond uncertainties. Note that the results of the two analysis periods are consistent with each other considering the relatively large uncertainties.

The present results demonstrate that excess ^{10}B is clearly present in the two chondrules analyzed, but ^{10}Be might not be alive at the time of the chondrule formation. The results may be interpreted in two ways: (1) chondrules or their precursors might be formed under strong irradiation conditions (e.g., near the active young Sun), where ^{10}Be was effectively produced, but later B isotopes became re-equilibrated within chondrules after (almost) complete decay of ^{10}Be, or (2) chondrules formed far from the Sun, where no strong irradiation conditions were available, but some of the precursor materials of chondrules contained carriers of excess ^{10}B, which became re-distributed throughout the chondrules during their formation episodes. The first scenario may be unlikely, because chondrule formation regions might be spatially or chronologically separated from the CAI forming regions. In the second scenario, a possible candidate for the carrier of excess ^{10}B would be CAIs or CAI-related materials. However, a careful consideration may be required if the elevated $^{10}B/^{11}B$ ratios can be explained by mixing of normal B (contained in most of the precursor materials of chondrules) and B with excess ^{10}B carried by CAI-like materials. Further studies are required to better understand the distribution of ^{10}Be (and carriers of excess ^{10}B) in the early solar system.

References: [1] Korschinek G. et al., *Nuclear Instruments and Methods in Physics Research*, B268:187-191, 2010. [2] Yoshida T. et al., *The Astrophysical Journal*, 686:448-466, 2008. [3] Banerjee P. et al., *Nature Communications*, 7:13639, 2016. [4] McKeegan K. D. et al., *Science*, 289:1334-1337, 2000. [5] Sugiura N. et al., *Meteoritics & Planetary Science* 36, 1397-1408, 2001. [6] MacPherson G. J. et al., *Geochimica et Cosmochimica Acta*, 67:3165-3179, 2003. [7] Wielandt D. et al., *The Astrophysical Journal Letters,* 748:L25 (7pp), 2012. [8] Gounelle M. et al. *The Astrophysical Journal Letters*, 763:L33 (5pp), 2013. [9] Fukuda et al., *Metsoc, Abstract* #6210, 2017. [10] Krot A. N. et al., *Geochimica et Cosmochimica Acta* 73 4963–4997, 2009. [11] Alexander C. M. O'D. and EBEL D. S., *Meteoritics & Planetary Science* 47, 1157–1175, 2012. [12] Sugiura N. et al. *Lunar and Planetary Science* XXXII, Abstract #1277, 2001. [13] Fukuda et al. *Geochemical Journal* 52, 255-262, 2018. [14] Zhai M. et al., *Geochimica et Cosmochimica Acta*, 60:4877-4881, 1996.