THE Be-B, Al-Mg AND OXYGEN ISOTOPES SYSTEMATICS OF ISHEYEVO (CH/CB) CALCIUM-, ALUMINIUM-RICH INCLUSIONS. Matthieu Gounelle[1], Marc Chaussidon[2], and Claire Rollion-Bard[2]. [1]Laboratoire de Minéralogie et de Cosmochimie du Muséum, CNRS & MNHN, UMR 7202, CP52, 57 rue Cuvier, 75 005 Paris, France. [2]Centre de Recherches Pétrographiques et Géochimiques, CRPG-CNRS, BP 20, 54501,Vandoeuvre-les-Nancy Cedex, France (gounelle@mnhn.fr).

Introduction: Short-lived radionuclides (SRs) are radioactive elements with half-lives of ~ 1 Myr. Some SRs were present in the protoplanetary disk at abundances substantially higher than the levels expected for average interstellar medium [1]. The origin of SRs is highly debated, because it has important consequences for early solar system chronology, planetesimal heating and the astrophysical environment in which our solar system was born. Among SRs, ^{10}Be (which decays to ^{10}B with a recently remeasured half-life $T_{1/2}$ = 1.4 Myr [2]) plays a special role because, unlike i.e. ^{26}Al ($T_{1/2}$ = 0.74 Myr), it cannot be produced by stellar processes [3]. To account for the high abundance of ^{10}Be in the solar system, two kinds of models exist. Desch et al. [4] suggested that it was delivered within the dense core progenitor of our solar system by interstellar Galactic Cosmic Rays (GCRs). Alternatively, ^{10}Be was produced within the solar system via the interaction of solar energetic particles with gas and/or dust in the protoplanetary disk [3, 5-7].

The abundance of ^{10}Be in the early solar system is poorly known. In Calcium-, Aluminium-rich Inclusions (CAIs) from the CV3 meteorites (having a "canonical" ^{26}Al abundance), the ratio ^{10}Be/^{9}Be was ~ 0.8 x 10^{-3} [8-11]. In the refractory hibonites (which lack ^{26}Al) from the CM2 chondrite Murchison, the initial ratio ^{10}Be/^{9}Be was ~ 0.5 x 10^{-3} [12-14]. These pioneering data suggest that ^{10}Be abundance in the early solar system is decoupled from that of ^{26}Al [12, 13].

We have undertaken a systematic study of the Be-B and Al-Mg systematics in the Isheyevo (CH/CB) CAIs. Oxygen isotopes were also measured for each inclusion. CAIs from Isheyevo were chosen because of their ultrarefractory mineralogy, indicative of a primitive nature, and because most of them do not contain ^{26}Al [15] and are thefore believed to have formed very early in the protoplanetary disk [16]. These *combined measurements* will shed a light on the distribution of ^{10}Be within the protoplanetary disk, on its origin, as well as on its relationship to ^{26}Al.

Experimental methods: Mineralogy of CAIs was determined using Scanning Electron Microscopy at MNHN and Electron Microprobe at the Université Paris 6. The B-Be concentrations and isotopic compositions were measured with the Nancy ims 1270 and 1280 ion microprobes according to procedures previously described [9]. Primary intensities of ~ 5 nA were used, which correspond to beam sizes of up to 25 µm in diameter. Special attention was paid to avoid spots where some localized enhanced concentrations of B were observed during the pre-sputtering (possibly due to contamination in cracks). The Be-B concentrations were directly determined from the secondary beam intensities normalized to the primary beam intensity. The Be/B elemental ratio was determined using an hibonite (Madagascar) standard. Errors on isotopic and elemnetal ratios are given with 1 sigma error bars. Isotopic ratios were calculated following the approach of [17], i.e. ratioing the total number of counts. Data are reported using the notation $\delta^{10}B = ((^{10}B/^{11}B)/(^{10}B/^{11}B)_c-1) \times 1000$.

Mg isotopic compositions were measured in monocollection mode using an electron multiplier at a mass resolution of ~5000. A set of standards (silicates, glasses, hibonites) were used to calibrate instrumental mass fractionation for Mg isotopes and the Al/Mg ion yield. The external reproducibility for the measurement of ^{26}Mg excess is better than +1.5‰ (2 s.d.). Because most of the samples are Mg-poor, the precision of the measurements is limited by counting statistics to ±5‰.

Oxygen isotopic measurements were made in multi-collection mode using classical procedures previously described [18].

Results: All nine studied CAIs were found in the CH lithology of the Isheyevo chondrite. They have a mineralogy typical of that of CH chondrites [16, 19]: they are spinel-, hibonite- and grossite-rich. They contain minor amounts of pyroxene, melilite and perovskite.

The boron isotopic composition of Isheyevo CAIs varies between δ^{10}B = -37 ‰ and 633 ‰. Elemental ^{9}Be/^{11}B ratios vary between 0.05 and 18. Eight CAIs contain no detectable ^{26}Al, while CAI #2009 formed with ^{26}Al/^{27}Al ~ 4 x 10^{-5}. Δ^{17}O range from -21 to -24 ‰. As far as the Be-B systematics is concerned, CAIs can be divided into 4 distinct groups. **(A)** Four CAIs contain no boron isotopic excesses relative to chondrites. These CAIs have also low Be/B ratios. They are exemplified by CAI #2009 (Fig 1a). Were ^{10}Be present when these CAIs formed, it would be undetectable given the low Be/B ratios and the large error bars on the boron isotopic composition. **(B)** CAIs #2012 and #2010 (Fig. 1b) show moderate excesses of ^{10}B relative to the chondritic composition (up to δ^{10}B = 64 ‰). The linear correlation between the ^{10}B/^{11}B isotopic ratio and the ^{9}Be/^{11}B elemental isotopic ratio might indicate the past presence of ^{10}Be at a level close to that observed by [8, 9] for CV3 CAIs, though with an initial $(^{10}B/^{11}B)_0$ ratio lower that what is observed for CV3 CAIs. **(C)** CAIs #2006 and #417 (Fig. 1c) have large excesses of ^{10}B relative to the chondritic composition (up to $\delta^{10}B$ = 163 ‰). The linear correlation between the $^{10}B/^{11}B$ ratio and the $^{9}Be/^{11}B$ elemental ratio might indicate the past presence of ^{10}Be at levels of $^{10}Be/^{9}Be$ = (8.6 ± 2.6) x 10^{-3} and (5.3 ± 1.1) x 10^{-3} respectively, with intercepts of $(^{10}B/^{11}B)_0$ = 0.22983 ± 0.00604 and $(^{10}B/^{11}B)_0$ = 0.23832 ± 0.00168 respectively. **(D)** CAI #411 (Fig. 1d) has ^{10}B excesses as large as 633 per mil relative to the chondritic composition. If the correlation between the $^{10}B/^{11}B$ ratio and the $^{9}Be/^{11}B$ elemental ratio is interpreted as an isochron, it would yield an initial ratio as large as $^{10}Be/^{9}Be$ = (15.6 ± 1.8) x 10^{-3}, with an intercept of $(^{10}B/^{11}B)_0$ = 0.25218 ± 0.00185.

Discussion: The low $\Delta^{17}O$ of observed CAIs indicate that they have suffered little metamorphism [20], and that the Be-B measured systematics have probably been little disturbed.

If the data are interpreted as isochrons, it yields surprising high initial $^{10}Be/^{9}Be$ ratios for groups (C) and (D). It would be as large as 15 times the highest ratio observed in CV3 chondrites, $^{10}Be/^{9}Be$ = (1.07 ± 0.48) × 10^{-3} [21], and 30 times higher than the initial value found of 0.5 x 10^{-3} found in CM2 hibonites [12, 13]. In the context of the interstellar model for the origin of ^{10}Be [3], where ^{10}Be can be used as a chronometer, it would mean that CAIs formation has spanned 7 Myr, an unrealistic time given our knowledge of CAI formation mechanisms [22]. In the context of the irradiation origin of ^{10}Be, it would suggest either that proton fluxes were as large as 6 x 10^{11} cm^2/s or that irradiation times were as long as hundreds of years for some CAIs [23]. Chemical differences or exposure to different types of flares (impulsive vs. gradual) between Isheyevo CAIs and CV3/CM2 CAIs could also account for the difference in the initial ^{10}Be abundance [24]. These extreme conditions would be applicable to the formation region of Isheyevo CAIs only.

The correlation between the $^{10}B/^{11}B$ ratio and the $^{9}Be/^{11}B$ elemental ratio observed in CAIs from groups (C) and (D) can also be interpreted as a mixing between two boron reservoirs having a distinct isotopic composition. One of these reservoirs would have $^{10}B/^{11}B$ = 0.4, corresponding to the ratio expected for a pure proton irradiation process on ^{16}O targets [14]. In such a case, CAI #411 would be an irradiation endmember and it would be of the uttermost importance to look for other irradiation products within it.

Our data confirm the observation that ^{26}Al and ^{10}Be are decoupled [12, 13]. Because it is likely that ^{26}Al was injected during the molecular cloud phase [25], this observation argues against an interstellar origin of ^{10}Be as already advocated by [14].

Conclusions: Large ^{10}B excesses were found in Isheyevo CAIs. These excesses could record either the in situ decay of ^{10}Be or ^{10}B produced by spallation, or more likely a combination of the 2 effects. In either cases, Isheyevo CAIs record extreme irradiation conditions in the early solar system which will be modelized by the time of the conference.

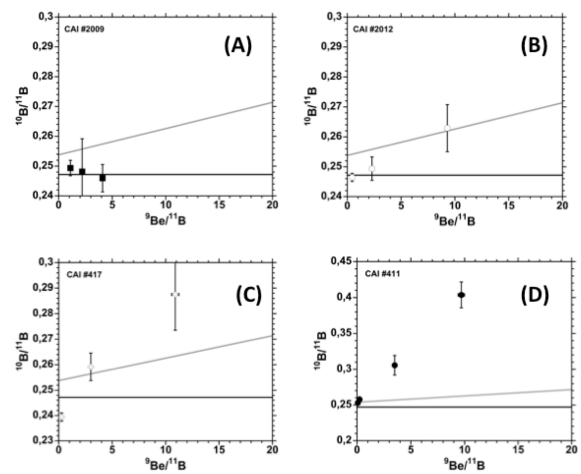

Fig 1: Variation of the boron isotopic composition of Isheyevo CAIs with the elemental Be/B ratio, for the 4 groups of CAIs discussed in the text. Errors are 1σ. The grey diagonal line is the best constrained isochron from CV3 chondrites, $^{10}Be/^{9}Be$ = 0.88 x 10^{-3} [9]. The dark horizontal line is the chondritic composition $(^{10}B/^{11}B)_c$ = 0.2472.

References: [1] M. Wadhwa, et al., in: Protostars and Planets V, B. Reipurth, D. Jewitt, et al., Eds., University of Arizona Press, Tucson, 2007, pp. 835. [2] J. Chmeleff, et al., *Nuc. Ins. Meth. B* 268 (2010) 192.[3] K.D. McKeegan, et al., *Science* 289 (2000) 1334.[4] S.J. Desch, et al., *ApJ* 602 (2004) 528.[5] M. Gounelle, et al., *APJ* 548 (2001) 1051.[6] I. Leya, et al., *APJ* 594 (2003) 605.[7] J. Duprat & V. Tatischeff, *ApJ* 671 (2007) L69.[8] K.D. McKeegan, et al., *LPSC* XXXII (2001) #2175.[9] M. Chaussidon, et al., *GCA* 70 (2006) 224.[10] N. Sugiura, et al., *MAPS* 36 (2001) 1397.[11] G.J. MacPherson & G.R. Huss, *GCA* 67 (2003) 3165.[12] M.-C. Liu, et al., *GCA* 73 (2009) 5051.[13] K.K. Marhas, et al., *Science* 298 (2002) 2182.[14] M.-C. Liu, et al., *ApJ* 719 (2010) L99.[15] A.N. Krot, et al., *ApJ* 672 (2008) 713.[16] H.W. Weber, et al., *GCA* 59 (1995) 803.[17] R.C. Ogliore, et al., *Nuc. Ins. Meth. B* 269 (2011) 1910.[18] M. Chaussidon, et al., *GCA* 72 (2008) 1924.[19] A.N. Krot, et al., *MAPS* 43 (2008) 1531.[20] M. Gounelle, et al., *ApJ* 698 (2009) L18.[21] M. Chaussidon, et al., *LPSC* 39 (2003) #1347.[22] E.D. Young, et al., *Science* 308 (2005) 223.[23] M. Gounelle, et al., *ApJ* 640 (2006) 1163.[24] M. Chaussidon & M. Gounelle, in: Meteorites and early solar system II, D.S. Lauretta and H.Y. McSween, Eds., University of Arizona Press, Tucson, 2006, pp. 323. [25] M. Gounelle, in: Star formation in the local universe, C. Charbonnel and T. Montmerle, Eds. 51, EDP Sciences, Paris, 2011, pp. 289.