The boron isotopic composition of the implanted solar wind in Itokawa grains: Technical development

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The Sun accounts for ~99.8% of the total Solar System mass. Therefore, knowledge of the elemental and isotopic abundances of the Sun, and thus by inference those of the solar nebula, are of fundamental importance, as such information sheds light on the astrophysical processes that took place during Solar System formation. The importance of the solar boron isotopic composition is that it provides a basis for understanding the evolution of this element in the Galaxy and in the Solar System. Since stellar nucleosynthesis processes destroy boron, the presence of this element in the universe is primarily derived from non-thermal nuclear reactions between energetic (>GeV) particles (protons and alphas) in the Galactic cosmic rays (GCRs) and C, N, and O nuclei in the interstellar medium (ISM) (e.g., [1]). However, the $^{11}B/^{10}B$ ratio of 2.5 in the GCRs, first predicted by [2] and then later confirmed by spacecraft measurements (e.g., [3]), falls short of the CI-chondrite value (4.04; [4]). Moreover, the boron isotopic compositions in the solar neighborhood determined by spectroscopy, albeit with large uncertainties ($^{11}B/^{10}B = 3.4 \pm 0.7$ in local diffuse clouds and $^{11}B/^{10}B = 3.7-4.7$ in the atmospheres of two nearby stars; e.g., [5−6]), are similar to that of the CI chondrites, implying that GCRs cannot be the sole source of boron and additional production mechanism(s), such as low-energy irradiation (e.g., [7]) and/or neutrino-spallation of ^{12}C during supernova explosions (e.g., [8]), are needed to account for the ^{11}B overabundance observed in the Solar System and elsewhere.

A wealth of bulk-chondrite data has shown that the average $\delta^{11}B$ value of each chondrite group (carbonaceous, ordinary, and enstatite) is only within a few permil of the CI-chondrite value (average $^{11}B/^{10}B = 4.04$; [4]). However, variations up to 25‰ in $\delta^{11}B$ are present both within individual chondrite groups and among the different chondritic meteorites ([4]; also see [9] for a detailed review). Large boron isotopic fractionations are known to occur between fluids and B-bearing minerals at low temperatures ([10]), and this might in part be responsible for the observed variations in chondritic meteorites. Given that CI chondrites have undergone severe aqueous alteration, how representative the CI $^{11}B/^{10}B$ ratio is of the solar value is called into question. It is therefore necessary to bring additional constraints from direct measurements of solar material. Literature data, albeit only a couple of them which are published in conference abstracts, have pointed to isotopically lighter boron isotopic compositions in the solar wind compared to that of CI chondrites, with $^{11}B/^{10}B = 3.78 \pm 0.06$ (−64±15‰) in a lunar soil sample [11] and 3.47±0.28 (−141±69‰) in the shallow layer of an unpolished Itokawa olivine grain returned by the Hayabusa mission [12]. Although the isotopically light solar wind is expected in the context of Insufficient Coulomb Drag (ICD), the degree to which boron isotopes would fractionate between the bulk Sun and solar wind is only ~40‰/amu (assuming a mean charge state of 5+; e.g., [12−14]), considerably smaller than the observed solar wind values. Given the excellent agreement between the ICD model predictions of oxygen, nitrogen and noble gases and *Genesis* data (e.g., [14−16]), it is reasonable to assume that the actual isotopic fractionation of boron in the solar wind is close to the model estimate. Therefore, the Sun could be marginally lighter than CI chondrites (and the solar nebula) by ~20‰ (after correcting for ICD effects), as was implied by the data of [11], or could be as negative as −100‰ in $\delta^{11}B$ (if using the result from [12]). Given the discrepancy in the literature data, a better understanding of the solar $\delta^{11}B$ would be highly desirable to constrain the origin and evolution of this element in the Solar System.

We will perform boron isotopic analysis of unpolished Hayabusa olivine and pyroxene grains will be performed on the UCLA CAMECA ims-1290 ion microprobe in multicollection depth profiling mode by using a primary O^- beam generated by the Hyperion-II RF oxygen plasma source. Analytical development for such measurements is currently underway. One key issue in determining the solar wind boron isotopic ratios in Hayabusa samples is the instrument sensitivity. A low concentration of solar-wind implanted boron in the Hayabusa surface grains is expected given its natural (cosmic) abundance being ~6 orders of magnitude lower than that of oxygen. Fujiya et al., (2016) [12] provided an upper limit of B fluence of 4×10^{11} ions cm^{-2} based on the surface irradiation ages of 10^2 to 10^5 years inferred from the solar flare track densities [17] and ^{20}Ne flux of the bulk solar wind at 1 AU inferred from the Genesis data [14]. Assuming a 200-nm implantation depth from the grain surface, one should anticipate at most ~100 ppb in total (if distributed homogeneously) of solar-wind B in this shallow region of a grain. Therefore, the mass spectrometer needs to be sensitive enough to detect weak secondary ion signals and to measure the isotopic compositions with reasonable precision. We have also performed a sensitivity test with a San Carlos olivine standard in depth profiling mode on the ims-1290. Multicollection of boron isotopes and $^{29}Si^{3+}$ (used as a matrix normalizing element for estimating the concentration) with electron multipliers is chosen in this application to measure low secondary ion intensities and to improve the analytical precision. A small field aperture (FA) was used to ensure that only signals from the center (15×15 μm^2) of a 25×25 μm^2 raster square were collected. After summing up the counts over the cycles where signals were stable, we obtained an intrinsic B abundance in the olivine of ~30 ppb, which corroborates the result of [18], and we measure chondritic $^{11}B/^{10}B = 3.95 \pm 0.24$ (2σ, after correction for instrumental mass fractionation). The error on the isotopic ratio is comparable to those obtained in phases of similar B abundance (e.g., some melilite crystals in CAIs) on other large-radius ion microprobes. We can expect slightly better precision for the solar wind B as the abundance is higher, albeit distributed in very shallow surface layers.

The test result demonstrates that the ims-1290 ion microprobe has the required sensitivity to measure very trace amounts of boron for isotopic ratios. However, there are two issues that must be further addressed to ensure the success of this proposition. First, the boron abundance estimated here is not based on a matrix-matched standard, but rather on a NIST616 glass. This could affect the relative sensitivity factor (RSF), and thus give rise to inaccurate quantification of elemental concentrations. We will follow the method used in [19] to develop proper standards by implanting ^{10}B into terrestrial olivine and pyroxene to better quantify the RSF. In contrast to the elemental RSF, we do not expect that matrix effects on the IMF will be a problem for boron as extensive investigations show at most permil level deviations for various silicate glasses of different chemical compositions [20], which is negligible compared to expected analytical uncertainty. Second, signals from surface contamination on olivine appeared to have lasted 60–80 analysis cycles (the "knock-on effect"). If we perform B isotope analysis on the Hayabusa grains the same way as we did in this test, the SW signals can be significantly diluted by surface contamination. Therefore, we will pre-sputter a large area on the grain surface using an ion beam with low impact energy to remove surface contamination without eroding away much of the material of interest, and has been proven effective in the oxygen analyses of Genesis samples [16]. We will work out the optimum conditions (beam intensity, impact energy, pre-sputtering time) on a ^{10}B-implanted San Carlos olivine standard, and then apply it to cleaning the surface contamination on the Hayabusa samples. Some preliminary data from the development will be presented in the symposium.

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