
I. Introduction

Contrary to other chemical elements, $^6$Li, $^{10}$B and $^{11}$B cannot be produced during the Big-Bang nucleosynthesis or inside stars by thermonuclear reactions. It has been proposed that these nuclides were the resulting products of spallations reactions which would occur at high energies (up to Gev) between the Galactic Cosmic Rays and atoms of the interstellar medium [1]. Models predicts a $^{11}$B/$^{10}$B isotopic ratio of 2.5, that is very different from that observed on Earth or in chondrites ($^{11}$B/$^{10}$B = 4.0) [2]. Recently, boron isotopic variations up to 70% have been detected in individual chondrules of Semarkona (LL3), Hedjaz (L3-5) and Allende (CV3) [3].

The correlations observed between the $^{11}$B/$^{10}$B ratios and the B concentrations are interpreted as the result of a mixture of two components: a $^{11}$B-rich boron in the pre-solar interstellar cloud, produced by spallation reactions at low energy (10-30 Mev) and a $^{11}$B-depleted component which represents the $^{11}$B/$^{10}$B of the cloud before its irradiation. The isotopic compositions of these two components are highly model dependent and still subjected to debate [4, 5]. Nuclear collisions between H (and He) at rest in the cold interstellar cloud and Oxygen/Carbon originated from super-novae in the core of the cloud, would produce the $^{11}$B-rich end-member. Such a mechanism has been recently detected in Orion [6] and according to the spallation rates (deduced from the de-excitation rates of the carbon nuclei) most of the solar system $^{11}$B-rich boron would have been synthesised within few million years before the formation of the nebula [3,4].

II. New developments

We report here the preliminary results of tests concerning two major implications of our interpretation of the boron isotope variations. (1) Freshly nucleosynthetized boron with variable $^{11}$B/$^{10}$B ratios must have been preserved as solid grains in the solar nebula and implanted or embedded in the newly formed chondrules. Therefore, chondrules cooling rates do not allow a complete isotopic homogenisation. (2) Another element, lithium, is also formed by these spallogenic reactions with a spallogenic isotopic ratio ($^7$Li/$^6$Li) between 2 and 5 according to different models, which is lower than the bulk solar system ratio of $= 12.5$. Therefore, a negative correlation between the isotopic compositions of Li and B should be present in chondrules.

III. Isotopic calibrations, reproducibility and contamination tests

The $^7$Li/$^6$Li and $^{11}$B/$^{10}$B ratios were measured with the Nancy ion microprobe (Cameca ims3f). Instrumental mass discrimination was determined for Li and for B from the analyses of synthetic glasses either doped with the international NBS standards (LSVEC 8545 for Li and NBS 951 for B) or prepared from minerals with isotope ratios measured by mass spectrometry. The reproducibility on the $^7$Li and $^{11}$B is of $\pm 1.7\%$ and $\pm 1.6\%$ (1 sigma) respectively on the standard glasses, and of $\pm 3.3\%$ (8 analyses) and $\pm 5.9\%$ (47 analyses) on a terrestrial peridotite containing Li and B under the ppm level. This is a factor of $\approx 10$ smaller than found in chondrules.

Although terrestrial rocks with low B contents <1ppm prepared with the identical procedure than chondrites, have never shown any obvious contamination feature, we performed several severe tests to quantify the possible laboratory addition of B by cutting and polishing. One polished section was rinsed in ultrasonic bath with water containing pure $^{10}$B-boron. Water was then evaporated and the sample coated with gold and analysed for $^{11}$B/$^{10}$B ratio. In this particular case, it takes 200 min. sputtering for the $^{11}$B/$^{10}$B ratio to increase from 3.25 to the
uncontaminated value of 3.93 and the ratio then stays stable at this value for the next 400 minutes sputtering. This sample was then rinsed with the usual laboratory distilled water and alcohol, re-polish in order to remove about 5 μm in depth and analysed. The uncontaminated 11B/10B ratio of 3.93 is obtained immediately and stays constant for the next 400 min. sputtering, showing that the preparation procedure efficiently removes surface contamination.

IV. Isotopic equilibration rates

Two samples of carbonate and tourmaline, having respective δ11B values of +23 and -20.1 ‰ have been mixed with a MORB glass (0.44ppm B with a δ11B value of -3.1±1.5‰), the mixed powder containing ≈23% boron coming from the carbonate and ≈76% from the tourmaline. This corresponds to a bulk B content of 9.8 ppm and a bulk δ11B of -9±3‰. The powder was melted at 1600°C under the air during 1.5, 3 and 15 min. and quenched at room temperature. The glass obtained at 1.5 min. still shows considerable variations of δ11B (mean at -8.6±9.6‰, Fig 1) while the heterogeneity decreases regularly for longer melting durations (-10.3±5.4‰ at 3 minutes and -13.1±3.2‰ at 15 min). This shows clearly that isotopic homogenisation of boron is not reached completely during a few minutes heating event at 1600°C. Although, it is difficult to extend quantitatively these results to the measured δ11B heterogeneity found in chondrules because it depends on the δ11B of the two pure end-members before melting, it is quite clear that boron isotopic heterogeneity can be easily preserved during the formation of chondrules.

V. Correlated δ11B and δ7Li in chondrules

Our available data indicate that the predicted negative correlation between δ11B and δ7Li exists in some chondrules but is rather noisy. An interesting example is shown in Fig 2 for two chondrules from Hedjaz where a clear correlation can be observed between both δ11B and δ7Li and the “chemical regions” of the chondrule: the glass shows systematically low δ7Li and high δ11B and vice-versa for olivine. Although the correlation between δ11B and δ7Li is not perfect here, such a trend is in agreement with our spallogenic interpretation since it suggests that a 11B-rich and 7Li-depleted component was added to the chondrules and was not re-homogenised during the heating event that yielded the chondrule.