A Heterogeneous Solar Nebula as Sampled by CM Hibonite Grains. Ming-Chang Liu[1,2*], Marc Chaussidon[1], Christa Göpel[3], Typhoon Lee[4], [1]CNRS-CRPG, Nancy, France. (mcliu@crpg.cnrs-nancy.fr). [2]ASIAA, Taipei, Taiwan. [3]IPGP, Paris, France. [4]ASIES, Taipei, Taiwan.

Introduction: The degree of uniformity of isotope distribution in the solar nebula has long intrigued cosmochemists, as it is crucial not only for the use of short-lived radionuclides for chronometry but also for constraining their astrophysical sources. ^{26}Al (decays to ^{26}Mg, $t_{1/2}$ = 0.72 Myr), the most extensively studied short-lived radionuclide, is believed to have been homogeneously distributed in the early Solar System at the level of $^{26}Al/^{27}Al = 5.2\times10^{-5}$ (the "canonical" value, [1–3]) based on numerous Mg isotope measurements in meteoritic Ca-Al-rich Inclusions (CAIs), the oldest datable Solar System solids with an absolute radiometric age of 4.568 Gyr [4]. Such a canonical value has long been used to argue for homogeneity of ^{26}Al in the solar nebula, and therefore the validity of ^{26}Al chronology in the first several million years of the Solar System history (see review in [5]).

Hibonite ($CaMg_xTi_xAl_{12-2x}O_{19}$), primarily found in CM chondritic meteorites as 20−80 μm individual inclusions in the matrix, is believed to be one of the first Solar System solids from a thermodynamic perspective [6]. In equilibrium condensation, hibonite would condense out of the nebular gas at T = 1500−1750 K, comparable to or higher than the forming temperatures of CAI components (e.g., [7]). Therefore, they could potentially be older than usual CV CAIs. However, unlike CV CAIs in which a high degree of uniformity of ^{26}Al was found, the inferred ^{26}Al abundances split CM hibonite grains into two distinct groups that are correlated with their mineralogy and morphology [8]. The inferred $^{26}Al/^{27}Al$ ratio in individual Spinel-HIBonite spherules (SHIBs) shows an apparent scatter from ~5.5×10^{-6} to 8.7×10^{-5} (2σ), but is broadly consistent with ~5×10^{-5} within large analytical errors [8–10]. In contrast, PLAty hibonite Crystals (PLACs) lack resolvable ^{26}Mg excesses that can be attributed to ^{26}Al decay, but instead show small variations of $\Delta^{26}Mg^*$ (deviation from a mass dependent fractionation line) from +5‰ to −4‰, from which an upper limit of $^{26}Al/^{27}Al$ ~5×10^{-6} could be inferred.

The quantitative chronology for CM hibonite relative to CV CAIs still remains murky so far, as no absolute ages could be obtained due to small sample sizes and low uranium concentrations [9, 11]. It has been generally agreed that together with the associated large ^{48}Ca and ^{50}Ti anomalies, the lack of ^{26}Al in PLACs represents earlier formation than CAIs, probably before ^{26}Al was delivered into the Solar System [12]. However, the timing for SHIB formation is still ambiguous primarily because of large analytical uncertainties and the apparent scatter in $^{26}Al/^{27}Al$. To better understand the origin of this apparent scatter in $^{26}Al/^{27}Al$, high precision Mg isotope measurements in SHIBs are needed. We report the Mg isotope results in 43 new hibonite grains, in hopes of better understanding the distribution of ^{26}Al in SHIBs, and constraining the formation timescales of CM hibonite.

Experimental: The hibonite samples studied here were hand-picked from an acid residue of the Murchison meteorite prepared at the Univ. of Chicago (Courtesy of Andy Davis), and a high density fraction of the Paris meteorite separated at IPGP by using the freeze-thaw method. The Mg isotope measurements were performed on the CAMECA 1280HR2 at CRPG. Polished, epoxy-mounted grains were sputtered with a 20 nA, 13 KeV $^{16}O^-$ primary beam (ϕ ~ 30−35μm) to generate sufficient secondary ion intensities for accurate current measurement by multiple Faraday cups. The mass resolution (M/ΔM) was set at 2500 (slit #1) to separate interferences from the peaks of interest. Although $^{24}MgH^+$ could not be fully resolved from $^{25}Mg^+$ under such mass resolution, the steady vacuum condition (pressure ~ 2×10^{-9} torr), which was achieved by using liquid nitrogen, made the hydride contribution negligible (< 0.1‰). Instrumental mass fractionation was characterized with a suite of terrestrial standards, and corrected for by assuming an exponential law. The true $^{27}Al/^{24}Mg$ ratio was deduced for each measured grain by applying a relative sensitivity factor determined on a Madagascar hibonite standard.

Result and discussion: The Mg isotopic compositions of the 43 measured hibonite grains are reported in a Al-Mg isochron diagram (Figure 1). Because of small sample sizes and a relative large beam diameter in most cases, each measurement was analogous to "bulk" analysis. Hibonite broadly falls into two populations in correlation with their morphology, and no systematic difference could be found between Murchison and Paris hibonite. With high precision, SHIBs show resolvable ^{26}Mg excesses, but the scatter in $\Delta^{26}Mg^*$ values is too large to form a well-defined isochron. Therefore, an initial $^{26}Al/^{27}Al$ for each SHIB was inferred by a "two-point regression" method, i.e., connecting a SHIB point to the origin where $^{26}Mg/^{24}Mg = 0.13932$ and $^{27}Al/^{24}Mg = 0$. This yielded a range of inferred $^{26}Al/^{27}Al$ ratios from 6.6×10^{-6} to 6.2×10^{-5} (Figure 2). Although the upper end of this range corresponds to the supra-canonical value suggested by Young et al., (2005), it should be noted that roughly 60% of the hibonite grains measured have $^{26}Al/^{27}Al$ consistent with the canonical value of 5.2×10^{-5} within errors. Here we consider two possibilities that could have been responsible for the observed $^{26}Al/^{27}Al$ variations.

Isotopic disturbance: It has been generally agreed that lower $^{26}Al/^{27}Al$ ratios in refractory inclusions could have resulted from internal redistribution of Mg isotopes, as evidenced in many CAIs by having an elevated isochron intercept, or late-stage mineralogical alteration [13]. Therefore, it would be conceivable that SHIB grains with $^{26}Al/^{27}Al < 5.2\times10^{-5}$ also experienced partial loss of radiogenic ^{26}Mg. However, it is important to recognize that the SHIB analyses in this study were analogous to those of "whole-rock" CAIs, and thus should be insensitive to internal isotopic re-equilibration between spinel and hibonite. High temperature open-system isotopic perturbations are possible, such as diffusion of Mg from the inside out, and isotope exchange between SHIBs and the nebular gas. A correlation between $^{26}Al/^{27}Al$ and $\delta^{25}Mg$ should be expected in either scenario, as diffusion causes both Mg loss and isotope mass fractionation, and isotope exchange would lead to a mixing line. The scatter seen in our data cannot be explained by any of the two possibilities.

Early formation of SHIBs before CAIs: Calculations of equilibrium thermodynamics predicted that hibonite formation could have taken place earlier than that of CAIs. If the formation of SHIBs indeed followed this sequence, SHIBs must have sampled a part of pre-CAI solar nebula. Thus, the overall range of $^{26}Al/^{27}Al$ ratios observed in SHIBs could be understood in the context of heterogeneous distribution of ^{26}Al. The lack of extremely high values (e.g., $^{26}Al/^{27}Al$ much larger than 5.2×10^{-5}), and a gradual increase of $^{26}Al/^{27}Al$ from the galactic background level (~8×10^{-6}) to 6.2×10^{-5} (although overlapping 5.2×10^{-5} within errors) in our observation imply that SHIBs could not have formed simultaneously in the region(s) characterized by large ^{26}Al heterogeneity, but should instead have solidified steadily in a reservoir with relatively well-mixed and increasing $^{26}Al/^{27}Al$, before the complete homogenization of ^{26}Al in the whole solar nebula. The formation scenario most consistent with our hibonite data would be that a fraction of SHIBs formed in the inner part of the disk with $^{26}Al/^{27}Al$ at the galactic background level, followed by injection of ^{26}Al from an external source. While this radionuclide was still highly heterogeneous on the nebula scale, it was relatively well homogenized in the region(s) close to the Sun. As mixing progressed, the average $^{26}Al/^{27}Al$ in the nebula increased; therefore SHIBs that crystallized during this time could record increasing $^{26}Al/^{27}Al$. After $^{26}Al/^{27}Al$ was homogenized to the nebula-wide canonical level, the majority of SHIBs formed nearly contemporaneously with CV CAIs.

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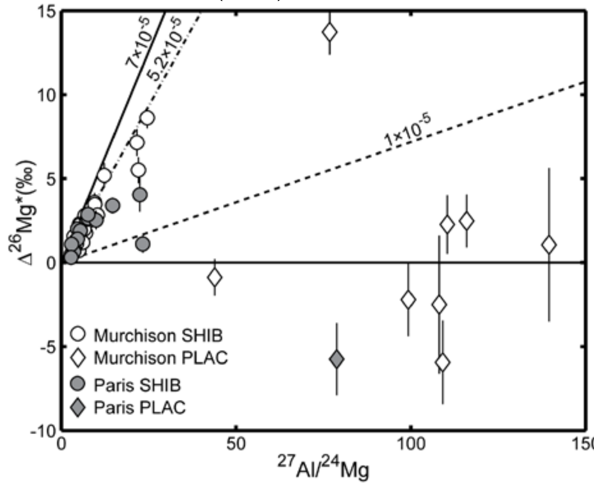

Figure 1: Magnesium isotopic compositions of 43 hibonite grains measured.

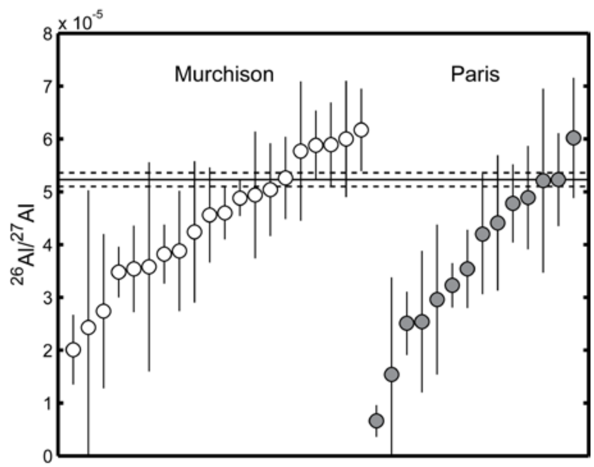

Figure 2: The inferred $^{26}Al/^{27}Al$ ratios for SHIBs from Murchison and Paris.