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New constraints on the relationship between ^{26}Al and oxygen, calcium, and titanium isotopic variation in the early Solar System from a multielement isotopic study of spinel-hibonite inclusions

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Abstract

We report oxygen, calcium, titanium and ^{26}Al–^{26}Mg isotope systematics for spinel-hibonite inclusions (SHIBs), a class of calcium–aluminum-rich inclusions (CAI) common in CM chondrites. In contrast to previous studies, our analyses of 33 SHIBs and four SHIB-related objects obtained with high spatial resolution demonstrate that these CAIs have a uniform Δ^{17}O value of approximately −23‰, similar to many other mineralogically pristine CAIs from unmetamorphosed chondrites (e.g., CR, CV, and Acfer 094). Five SHIBs studied for calcium and titanium isotopes have no resolvable anomalies beyond 3σ uncertainties. This suggests that nucleosynthetic anomalies in the refractory elements had been significantly diluted in the environment where SHIBs with uniform Δ^{17}O formed. We established internal ^{26}Al–^{26}Mg isochrons for eight SHIBs and found that seven of these formed with uniformly high levels of ^{26}Al (a multi-CAI mineral isochron yields an initial ^{26}Al/^{27}Al ratio of ~4.8×10^{-5}), but one SHIB has a smaller initial ^{26}Al/^{27}Al of ~ 2.5×10^{-5}, indicating variation in ^{26}Al/^{27}Al ratios when SHIBs formed. The uniform calcium, titanium and oxygen isotopic characteristics found in SHIBs with both high and low initial ^{26}Al/^{27}Al ratios allow for two interpretations. (1) If subcanonical initial ^{26}Al/^{27}Al ratios in SHIBs are due to early formation, as suggested by Liu et al. (2012), our data would indicate that the CAI formation region had achieved a high degree of isotopic homogeneity in oxygen and refractory elements before a homogeneous distribution of ^{26}Al was achieved. (2) Alternatively, if subcanonical ratios were the result of ^{26}Al–^{26}Mg system resetting, the clustering of SHIBs at a Δ^{17}O value of ~−23‰ would imply that a ^{16}O-rich gaseous reservoir existed in the nebula until at least ~0.7 Ma after the formation of the majority of CAIs.

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1. INTRODUCTION

Calcium-, aluminum-rich inclusions (CAIs) are the oldest dated objects that formed in the Solar System (Amelin et al., 2002; Connelly et al., 2012). Preserved within and delivered by primitive meteorites, CAIs provide a wealth of information about processes that occurred in the early Solar System, as well as the nature of the material that the Solar System originated from. For instance, resolvable mass-independent isotopic anomalies of CAIs can be linked to predicted nucleosynthetic signatures of evolved stars (e.g., Trinquier et al., 2009). Another example is that many CAIs attest to the presence of short-lived radionuclides (SLRs) like ^{26}Al in the early Solar System (e.g., Lee et al., 1976). Most isotopic studies of CAIs have been focused on the sizable examples found in CV chondrites, which promote the view that CAIs formed when ^{26}Al was at a high and uniform abundance in the solar nebula (canonical level of $\sim 5.2 \times 10^{-5}$; Jacobsen et al., 2008; MacPherson et al., 2012). However, with advancements in the analysis of smaller samples, an increasing number of CAIs from other chondrite groups has been studied. They show that many CAIs formed with lower than canonical levels of ^{26}Al (e.g., depletions of up to ~50% of the canonical ratio are common) or even without ^{26}Al (Krot et al., 2012, and references therein). Often, subcanonical levels of ^{26}Al are interpreted as formation or reprocessing after significant decay of ^{26}Al (e.g., for CV CAIs with ratios between 5.17×10^{-5} and 2.77×10^{-5}; MacPherson et al., 2012). However, compelling arguments have been made that a significant number of CAIs formed earlier than canonical CV CAIs, in spite of showing no evidence for incorporation of live ^{26}Al or having formed with subcanonical levels of ^{26}Al (e.g., $\sim(5.2 \pm 1.7) \times 10^{-8}$ for HAL; Fahey et al., 1987; Wood, 1998; Sahijpal and Goswami, 1998). Among these are the enigmatic FUN (fractionated and unidentified nuclear effects; e.g., Wasserburg et al., 1977) CAIs and the PLACs (platy hibonite crystals; e.g., Ireland, 1990). The large magnitudes of nucleosynthetic anomalies in these CAIs attest to their formation at an early stage of Solar System evolution, which was characterized by large isotopic heterogeneities. The lack of evidence for the initial presence of ^{26}Al among these CAIs suggests that this SLR was initially absent in the CAI formation region and was introduced at a later stage, possibly due to a late injection from a nearby star (Wood, 1998; Sahijpal and Goswami, 1998).

Most studies of PLACs also present data for the spinel-hibonite inclusions (SHIBs), likely because both types of CAIs are abundant in CM chondrites, contain hibonite, and are recovered using the same analytical protocols (MacPherson et al., 1980). In contrast to the ^{26}Al-free PLACs, SHIBs have variable inferred ^{26}Al/^{27}Al ratios ranging from zero to supracanonical, which could indicate that they formed while ^{26}Al was admixed into the Solar System (e.g., Liu et al., 2012). This interpretation is strengthened by the magnitude of nucleosynthetic anomalies in SHIBs, which are intermediate between the ^{26}Al-depleted PLACs and regular CAIs with canonical initial abundances of ^{26}Al (e.g., δ^{50}Ti ranges of >300‰ in PLACs, mostly within ±10‰ for SHIBs and up to ~1‰ in CV CAIs; Ireland, 1988, 1990; Sahijpal et al., 2000; Liu et al., 2009a; Trinquier et al., 2009). If true, this would make SHIBs key samples for understanding the processes that governed admixture of ^{26}Al and dilution of nucleosynthetic anomalies in the early Solar System. However, it remains unclear how the oxygen isotopes of SHIBs and PLACs fit into this picture. Many primitive CAIs have a Δ^{17}O ~ −23‰, with minor variations between ~−25‰ and −21‰ (e.g., CAIs from Acfer 094, CR chondrites, certain primary phases in CV CAIs and Wark-Lovering rims; Makide et al., 2009; Ushikubo et al., 2011; Bullock et al., 2012; Bodénan et al., 2014), suggesting they formed in a fairly uniform oxygen isotopic reservoir. In contrast, SHIBs and PLACs have been reported to be more variable in Δ^{17}O, ranging from approximately −28‰ to −15‰ (Liu et al., 2009a). Analogous to the larger degree of isotopic heterogeneity in calcium and titanium, SHIBs and PLACs appear to indicate that the solar nebula was also initially isotopically heterogeneous in oxygen. After formation of PLACs and SHIBs, this heterogeneity may have been erased by mixing and/or thermal processes, allowing formation of CAIs with largely uniform oxygen isotopic compositions. However, other studies report more variable Δ^{17}O values for CAIs and related materials (e.g., Itoh and Yurimoto, 2003; Simon et al., 2011; Park et al., 2012) and interpret the results in favor of coexistence and exchange between ^{16}O-poor and ^{16}O-rich reservoirs while CAIs formed. If true, this interpretation could also account for the reported oxygen isotopic variations in SHIBs and PLACs.

An issue with previous studies of SHIBs is that they were usually limited to a single spot analysis per CAI by secondary ion mass spectrometry (SIMS). This is particularly problematic for obtaining accurate initial ^{26}Al/^{27}Al ratios as well as oxygen isotope data in these samples. For example, ^{26}Al/^{27}Al ratios are usually inferred from model isochrons constructed from a single spot analysis (commonly referred to as bulk analysis) and an assumed initial magnesium isotopic composition for an intercept (i.e., terrestrial). Possible problems include (1) variations in the initial magnesium isotopic composition, (2) resetting (partial or complete; e.g., Simon and Young, 2011; MacPherson et al., 2012), and (3) contributions from alteration phases. As studies of PLACs indicate (e.g., Liu et al., 2009a), the assumption of isotopically uniform magnesium is not trivial for early Solar System materials, particularly if SHIBs formed early (e.g., Liu et al., 2012). As such, variations in the initial magnesium isotopic compositions translate