

ON THE RARITY OF NEBULAR MATERIALS WITH SOLAR OXYGEN ISOTOPES. L. Kööp^{1,2}, K. Nagashima³, A. M. Davis^{1,2,4}, and A. N. Krot³, ¹Dept. of the Geophysical Sciences, ²Chicago Center for Cosmochemistry, ⁴Enrico Fermi Institute, Univ. of Chicago, Chicago, IL, ³HIGP/SOEST, Univ. of Hawai‘i at Mānoa, Honolulu, HI (E-mail: koeop@uchicago.edu)

Introduction: NASA’s Genesis mission collected and returned with samples of solar wind to Earth. Isotopic measurements revealed that solar wind is ¹⁶O-rich compared to sampled planets (i.e., Earth, Mars) and asteroids. The Sun’s $\Delta^{17}\text{O}$ ($=\delta^{17}\text{O}-0.52\times\delta^{18}\text{O}$) value was inferred to be $-28.4\pm 3.6\%$ (2σ) [1]. While many nebular materials preserved in chondritic meteorites are more ¹⁶O-rich than Earth (e.g., [2–6]), compositions as ¹⁶O-rich as the Sun are exceedingly rare in the meteorite record. For example, most Ca-, Al-rich inclusions (CAIs), the oldest dated materials that formed in the Solar System [7], appear to have formed with a $\Delta^{17}\text{O}$ of $\sim -24\%$ to -23% [2–5], suggesting that a resolved difference exists between the Sun and many of these early formed objects.

Here, we report preliminary O, Ca, Ti, and ²⁶Al-²⁶Mg systematics for a rare CAI (1-2-4) from Murchison with solar O isotopic composition. We also explore the reasons for the scarcity of such objects in the meteorite record.

Methods: O, Al-Mg, and Ca-Ti isotopes were analyzed with the UH Mānoa ims-1280 with conditions similar to those reported in [8], [9], and [5,6,10], respectively.

Results: *Petrologic characteristics:* Mineralogically, CAI 1-2-4 resembles spinel-hibonite inclusions known as SHIBs in CM chondrites [11]. This angular, friable aggregate is $\sim 100\ \mu\text{m}$ across and consists of spinel and hibonite crystals (Fig. 1). Picked from an acid residue of Murchison, voids could be primary or the result of dissolution of silicate minerals. The hibonite grains in this CAI are zoned in MgO and TiO₂, as seen in many SHIBs [5], but usually not in PLAC-type hibonites [6].

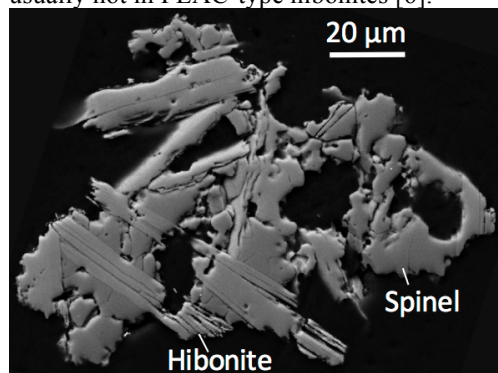


Figure 1. BSE image of CAI 1-2-4.

Oxygen isotopes: CAI 1-2-4 has a $\Delta^{17}\text{O}$ of $-29.1\pm 0.7\%$ (measured in both spinel and hibonite) and is thus as enriched in ¹⁶O as the Sun. The CAI plots slightly to the right of the carbonaceous chondrite anhydrous mineral (CCAM) line along a mass-dependent fractionation trend (Fig. 2).

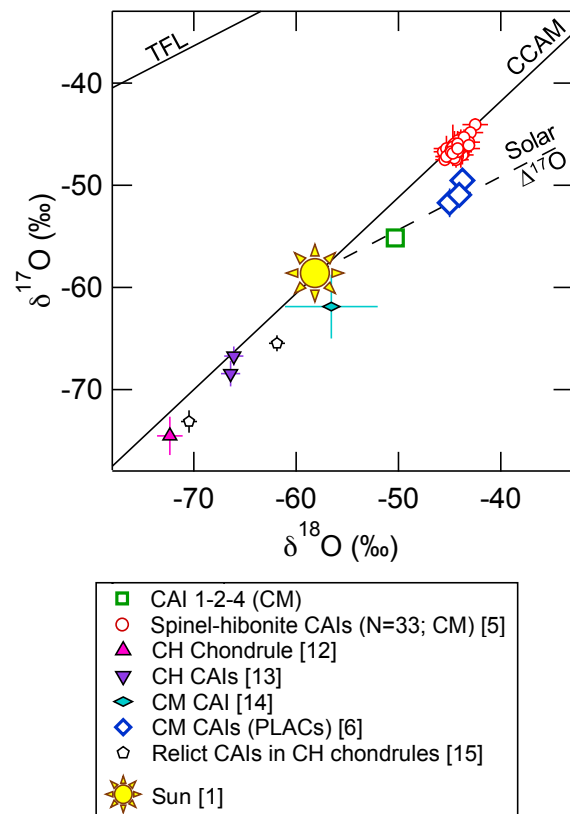


Figure 2. Comparison of O isotopes measured in CAI 1-2-4 with 33 other spinel-hibonite CAIs and with other ¹⁶O-rich Solar System objects, i.e., $\Delta^{17}\text{O}$ lower than common in CAIs.

Ca and Ti isotopes: Two analyses of CAI 1-2-4 reveal depletions in ⁴⁸Ca and ⁵⁰Ti ($-8.1\pm 3.3\%$ and $-11.8\pm 2.4\%$, respectively). These nucleosynthetic anomalies are larger than those in regular, ²⁶Al-rich CAIs from CV chondrites ($|\delta^{50}\text{Ti}|\leq 2\%$ [16]), but are of similar magnitude as those commonly found in FUN CAIs [10], for example. The magnitude of these anomalies is also comparable to ¹⁶O-rich PLAC hibonites [6], for which the range of anomalies decreases with increasing ¹⁶O content (from $>100\%$ at $\Delta^{17}\text{O} \sim -18\%$ to $<10\%$ at $\Delta^{17}\text{O} \sim -28\%$).

²⁶Al-²⁶Mg: Spinel and hibonite analyses show no correlated excesses in ²⁶Mg that would indicate incorporation of live ²⁶Al (Fig. 3). The inferred initial ²⁶Al/²⁷Al is $(0.4\pm 1.5)\times 10^{-6}$. The correlation line has a positive intercept ($\delta^{26}\text{Mg}^*_0 = 1.9\pm 0.2\%$), suggesting either resetting of the ²⁶Al-²⁶Mg system after decay (at least 3.3 Ma after formation of CAIs with canonical ²⁶Al/²⁷Al) or a Mg-iso-

tope anomaly. The latter would be consistent with nucleosynthetic Mg isotopic variation observed in other isotopically anomalous CAIs (e.g., PLAC hibonites and FUN CAIs [e.g., 17]).

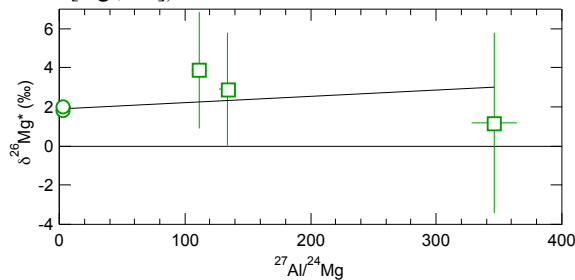


Figure 3. Al-Mg isochron diagram for CAI 1-2-4.

Discussion: Relationship to other SHIBs: While the mineralogy and hibonite mineral chemistry of CAI 1-2-4 resemble those of other CM SHIBs, its isotopic characteristics are unusual. The ^{16}O -enrichment of CAI 1-2-4 is in stark contrast to the 33 SHIBs studied by [5], which cluster at a $\Delta^{17}\text{O}$ of $\sim -23\%$ (Fig. 2a). Twelve of the 33 SHIBs with a $\Delta^{17}\text{O}$ of $\sim -23\%$ have been studied for Ca and Ti isotopes and show no or only marginally resolved anomalies, which is in contrast to the ^{48}Ca and ^{50}Ti depletions found in CAI 1-2-4. The ^{26}Al -poor character is also in contrast to 8 of the 33 SHIBs which were studied for the ^{26}Al - ^{26}Mg system and were found to have $^{26}\text{Al}/^{27}\text{Al} > 1 \times 10^{-5}$ [5]. Isotopically, CAI 1-2-4 is more consistent with PLAC hibonites [6].

^{16}O -rich objects in the meteorite record: CAI 1-2-4 is one of the rare known objects that are as ^{16}O -rich as the Sun. Other objects include a few PLAC hibonites ($\Delta^{17}\text{O}$ between $\sim -26.8\%$ and -28.4% [6]), two hibonite-corundum-bearing objects (A77307-COR-1: $-32.6 \pm 3.2\%$ [18]; BB-5: $-32.5 \pm 4.0\%$ [14]). Five CH chondrite inclusions are more ^{16}O -rich than the Sun ($\Delta^{17}\text{O} \sim -37$ to -32%): a chondrule [12] and four CAIs (two are relicts found in chondrules) [13,15].

The rarity of nebular materials with solar or even more ^{16}O -enriched compositions is not understood. It is noteworthy that CAIs with solar $\Delta^{17}\text{O}$ tend to be among the most refractory examples, but many similarly refractory objects are less enriched in ^{16}O , similar to regular CAIs.

Rarity of ^{16}O -rich CAIs and clustering of others: In self-shielding models (e.g., [19]), the average O isotopic composition of solids is assumed to be solar. In such models, rare CAIs with solar O isotopes could represent objects that (1) formed prior to onset of self-shielding or arrival of ^{16}O -poor water in the CAI formation region, (2) equilibrated with both ^{16}O -rich CO and ^{16}O -poor H_2O at high temperatures, or (3) formed relatively close to the UV source in a region where the wavelength responsible for C^{16}O dissociation had not yet been absorbed. The rarity of ^{16}O -rich objects could perhaps be attributed to an

early formation in scenario 1. However, the vast majority of CAIs have nonsolar O isotopes, indicating that the evolution of solids to ^{16}O -poor compositions had already begun when such CAIs formed. What is puzzling in the self-shielding model is the high frequency of CAIs with a limited range of $\Delta^{17}\text{O}$ values around $\sim -23\%$. Such values are found in both ^{26}Al -rich [3–5] and in some ^{26}Al -poor, isotopically anomalous CAIs [6,10,20], suggesting that conditions were favorable for forming CAIs with uniform, nonsolar O isotopic compositions for an extended period of time or in different regions of the disk.

Alternatively, O isotopic variation may have been primarily driven by inheritance of isotopically distinct primordial gas (^{16}O -rich) and dust (^{16}O -poor) reservoirs [20], ('presolar reservoirs model'), which was favored by [6] due to a relationship between O isotopes and nucleosynthetic anomalies. In this model, CAIs with solar O isotopes represent objects that formed after complete equilibration between primordial dust and gas (e.g., due to full evaporation of primordial dust at a solar dust to gas ratio). The rarity of ^{16}O -rich objects could then be explained if most materials preserved in meteorites formed in a region with dust to gas ratios above solar (e.g., after settling of dust in the midplane) or if temperatures were mostly too low to facilitate efficient equilibration with ^{16}O -rich CO.

Conclusions: We have found a CAI with solar O isotopes, anomalies in ^{48}Ca and ^{50}Ti , and low $^{26}\text{Al}/^{27}\text{Al}$. It is one of the rare examples of Solar System solids that are as ^{16}O -rich as the Sun.

The reasons for the scarcity of solar CAIs and the clustering of many CAIs at comparably ^{16}O -depleted compositions remain unclear. Explanations for the scarcity may be found in the self-shielding and presolar reservoirs models, but the clustering remains a puzzling observation in both models.

References: [1] McKeegan K. D. et al. (2011) *Science*, 332, 1528-1532. [2] Makide K. et al. (2009) *GCA*, 73, 5018-5050. [3] Ushikubo et al., 2011. [4] Bullock et al. (2012), [5] Kööp L. et al. (2016) *GCA*, 184, 151-172. [6] Kööp L. et al. (2016) *GCA*, 189, 70–95. [7] Connelly J. N. et al. (2012) *Science*, 338, 651–655. [8] Nagashima K. et al. (2015) *GCA* 151, 49–67. [9] Park C. et al. (2017) *GCA*, 201, 6–24. [10] Kööp L. et al. (2018) *GCA*, 221, 296–317. [11] Ireland T. (1988) *GCA*, 52, 2827-2839. [12] Kobayashi K. et al. *Geochem. J.*, 37, 663 (2003). [13] Gounelle M. et al. (2009) *ApJ*, 698, L18–L22. [14] Fahey A. J. et al. (1987) *ApJ*, L91–L95. [15] Krot et al. (2017) *GCA*, 201, 185–223. [16] Davis A. M. et al. (2018) *GCA*, 221, 275–295. [17] Liu M.-C. et al. (2009) *GCA*, 73, 5051-5079. [18] Bodénan J.-D. et al. (2014) *LPI Contrib. 1777*, #2025. [19] Lyons J. R. & Young E. D. (2005) *Nature*, 435, 317–320. [20] Krot A. N. et al. (2010) *ApJ*, 713, 1159–1166.