CALCIUM AND TITANIUM ISOTOPE SYSTEMATICS IN REFRACTORY INCLUSIONS FROM CM, CO, AND CR CHONDRITES.

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Introduction: Calcium-aluminum-rich inclusions (CAIs) are the oldest dated materials that formed in the Solar System [1]. They also preserve larger nucleosynthetic anomalies than later-formed Solar System objects [1,2]. Nucleosynthetic anomalies are commonly observed in coarse-grained igneous CAIs from CV chondrites [e.g., 2], in FUN CAIs (fractionated and unidentified nuclear effects) [3 and ref. therein], and in hibonite-rich CAIs from CM chondrites [4–7]. In contrast, the degree of nucleosynthetic variations in CAIs from other chondrite groups is not well constrained. Here we report on Ca and Ti isotopic compositions of 24 CAIs from CM, CO, and CR chondrites.

Methods: Calcium and titanium isotopic compositions were determined by secondary ion mass spectrometry using the Cameca ims-1280 at the University of Hawaiʻi. The protocol was similar to that reported previously [6,7]. For Ca- and Ti-rich phases (hibonite, Al,Ti-pyroxene), isotopic compositions of both elements were measured, but for Ti-poor phases (melilite and sometimes grossite), only Ca isotopes were measured.

Samples: The CM CAIs were separated from Murchison (Field Museum specimens ME 2752 and ME 2644) and include SHIBs (spinel-hibonite-inclusions), a melilite-rich CAI (previously described in [7]); a mass-fractionated grossite-rich CAI, and two single hibonite crystals. The CO CAIs include two concentrically zoned objects (31-2 from DOM 08006 and 16-1 from DOM 08004) consisting of, from inside outward, hibonite, grossite, spinel, perovskite, melilite, clinopyroxene, enstatite, and forsterite [8,11]. The other CO CAIs studied are two hibonite-grossite-rich objects (56-1 from DOM 08006 and 26-1 from DOM 08004; reported in [8]) and the Sc-rich Ornans CAI OSCAR [9]. The CR CAIs are from El Djouf 001 (MK #5), GRA 95229 (-17 #7), and Gao-Guenie (b) (FUN CAI #3). The mineralogy, O and Al-Mg isotopic systematics of the CR CAIs have been previously reported in [10].

Results: *CM CAIs*: Of the 15 studied objects, only two have clearly resolved anomalies in ^{48}Ca and/or ^{50}Ti. These are a spinel-hibonite object (δ^{48}Ca ~ δ^{50}Ti ~ –8‰), for which O and Al-Mg systematics are not yet known, and a single hibonite crystal (δ^{50}Ti 4.3±2.6‰). Another single hibonite crystal is mass-dependently enriched in heavy Ca and Ti isotopes, but has no resolved nucleosynthetic anomalies.

CO CAIs: The two concentrically zoned CAIs have clearly resolved anomalies: 16-1 (δ^{48}Ca ~ –27‰, δ^{50}Ti ~ –30‰) and 31-2 (δ^{48}Ca ~ 11‰, δ^{50}Ti ~ 4‰). Hibonite, grossite, and Al,Ti-diopside were analyzed individually in both CAIs (melilite in 31-2 as well), which revealed no variations between different minerals within the same CAI. Anomalies were also found in the two hibonite-grossite-rich CAIs: 56-1 (δ^{48}Ca ~ –10‰, δ^{50}Ti ~ 0‰) and 26-1 (δ^{48}Ca ~ –21‰, δ^{50}Ti ~ –30‰). OSCAR has no resolved anomalies in ^{48}Ca and ^{50}Ti.

CR CAIs: No resolved anomalies were found in the ^{26}Al-rich CAI GRA 95229-17 #7. The ^{26}Al-poor CAI El Djouf 001 MK #5 has a large ^{48}Ca excess (~20‰). The FUN CAI Gao-Guenie (b) #3 also has a large ^{48}Ca excess (27‰).

Discussion and Conclusion: Our study of CAIs from three different chondrite types shows that large nucleosynthetic anomalies can be found in CAIs from all three chondrite groups, and are, therefore, not limited to CM hibonites. For a subset of the studied CAIs, Al-Mg systematics have been previously reported [7,8,10]. Combined with our new Ca and Ti isotope measurements, the data for CM, CO, and CR chondrite CAIs are generally consistent with the mutual exclusivity relationship between large nucleosynthetic anomalies and incorporation of considerable amounts of live ^{26}Al. A possible exception may be FUN CAI Gao-Guenie (b) #3, which has a large ^{48}Ca excess in spite of a possibly relatively high inferred ^{26}Al/^{27}Al ((2.0±1.7)×10^{-5} [10]).

The CO CAIs 31-2 and 56-1 have been interpreted as equilibrium condensates [11]. If true, the sizable nucleosynthetic anomalies in these two CAIs suggest that nucleosynthetic anomalies were preserved in the gas phase, likely due to large-scale nucleosynthetic heterogeneity in the early Solar System. The lack of isotopic variation between different phases would suggest that no significant dilution took place during condensation.

References: [1] Connelly J. N. et al. (2012) *Science* 338:651–655. [2] Trinquier A. et al. (2009) *Science* 324:374. [3] Krot et al. (2014) *Geochimica et Cosmochimica Acta* 145:206–247. [4] Ireland T. R. (1990) *Geochimica et Cosmochimica Acta* 54:3219-3237. [5] Liu M.-C. et al. (2009) *Geochimica et Cosmochimica Acta* 73:5051–5079. [6] Kööp L. et al. (2016a) *Geochimica et Cosmochimica Acta* 189:70–95. [7] Kööp L. et al. (2016b) *Geochimica et Cosmochimica Acta* 184:151–172. [8] Simon S. B. et al. (2017) *Lunar & Planetary Science* 48:#1083. [9] Davis A. M. (1984) *Meteoritics* 19:214. [10] Makide K. et al. (2009) *Geochimica et Cosmochimica Acta* 73:5018–5050. [11] Simon S. B. (2016) 79th Annual Meeting of the Meteoritical Society. Abstract #6098.