TITANIUM ISOTOPES IN REFRACTORY INCLUSIONS FROM CO AND CM CHONDRITES. J. Render, S. Ebert, C. Burkhardt, T. Kleine, and G.A. Brennecka, Institut für Planetologie, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (jan.render@wwu.de)

Introduction: Ca-Al-rich inclusions (CAIs) are refractory mineral assemblages and the oldest dated solids that formed inside the Solar System. Although their formation is generally tied to high-temperature processes occurring near the young Sun, they are found primarily in outer Solar System materials, including chondrites, interplanetary dust particles, and comets. This being the case, understanding the origin and subsequent distribution of CAIs promises insights into the earliest stages of the Solar System and the processes taking place therein. However, this endeavor is complicated by mineralogically, chemically, and isotopically different subtypes of refractory inclusions, such as hibonite-rich grains (*e.g.*, PLACs & SHIBS), the enigmatic group of FUN-CAIs, and the more common 'regular' CAIs, whose relationships among one another are poorly constrained.

In recent years, mass-independent isotope anomalies of nucleosynthetic origin have proven to be a powerful tool to constrain genetic links among extraterrestrial materials, as they trace distinctive signatures of the underlying source reservoir and are not easily overprinted. Until recently, however, nucleosynthetic isotope anomalies have been almost exclusively explored in (1) large-sized CAIs from CV chondrites (particularly from the widely available Allende meteorite) using high-precision mass spectrometry [1], or (2) in sub-mm-sized hibonite-rich grains from the Murchison CM2 chondrite employing far less precise *in-situ* analyses [*e.g.*, 2-4].

Here we aim to address this issue by performing high-precision isotopic analyses of CAIs from CO and CM chondritic meteorites. Because these inclusions are considerably smaller compared to previously investigated CV CAIs, the element of interest needs to be present in weight percent levels, making titanium (Ti) an attractive target for the type of study. Additionally, Ti has five stable isotopes (^{46}Ti, ^{47}Ti, ^{48}Ti, ^{49}Ti, and ^{50}Ti) which are formed in different nucleosynthetic environments and, hence, could provide additional information about the origin of nucleosynthetic isotope anomalies in CAIs.

Samples and Methods: Twelve CAIs from five different CO3 chondrites (DaG 005, DaG 025, DaG 027, DaG 083, and NWA 2187) with diameters of several hundred µm and ten CAIs (most <300 µm) from the CM2 chondrite Jbilet Winselwan were selected for this study. Two inclusions from Jbilet Winselwan (termed '*JW-4*' and '*JW-7*') are of particular interest, as they consist of intergrown laths of hibonite and spinel, bearing mineralogical resemblance to the previously mentioned individual PLAC and SHIB crystals. All samples were identified and characterized using a JEOL 6610-LV SEM at the University of Münster, and subsequently removed using a *New Wave Research Micro Mill* [5]. After digestion, the samples were purified using a two-stage ion exchange chromatography following [6] and measured using the Neptune *Plus* MC-ICPMS in Münster, as outlined in [7]. Due to small sample sizes, solutions were measured at Ti concentrations between 50 and 100 ppb. When normalizing to ^{49}Ti/^{47}Ti to correct for mass bias, this results in a sub-ε analytical uncertainty for ε^{46}Ti, ε^{48}Ti, and ε^{50}Ti. This is roughly a 100-fold increase in precision compared to *in-situ* methods, with which such small samples previously had to be investigated.

Results: Titanium isotope compositions of the samples analyzed here are shown in Figures 1 and 2, along with literature data for 49 Allende CAIs from [8] and two CK CAIs from [9] in Figure 1. All investigated regular CAIs (*i.e.*, excluding JW-4 and JW-7) from CO and CM chondrites exhibit resolved excesses in ε^{50}Ti, and 17 out of 20 show positive isotope anomalies in ε^{46}Ti. The vast majority of these CAIs plot within uncertainty of the correlation line defined by an array of 49 CAIs from the Allende meteorite, where $\varepsilon^{46}\text{Ti} = (0.162 \pm 0.03) \times \varepsilon^{50}\text{Ti} + (0.15 \pm 0.27)$ [8]. To our knowledge, CAI sample JW-6 has the lowest ε^{50}Ti value ever reported for any regular CAI and appears to be the first such sample with a resolved deficit in ε^{46}Ti (Figure 1). The two exceptional inclusions JW-4 (consisting largely of hibonite) and JW-7 (consisting largely of spinel) in contrast show highly anomalous Ti isotopic compositions and plot far away from the correlated array of regular CAIs (Figure 2).

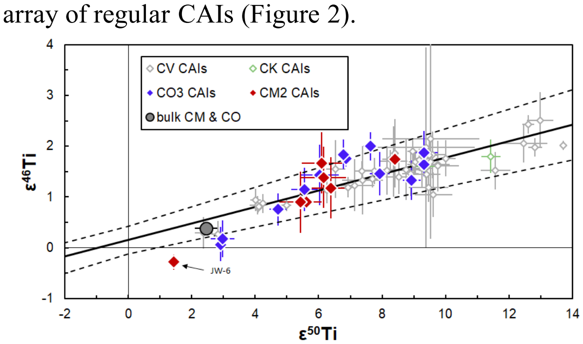

Figure 1: Nucleosynthetic Ti isotopic compositions of CAIs from CO and CM chondrites, along with literature data for CV CAIs [8] and for two CK CAIs [9] (JW-4 and JW-7 shown in Fig. 2).

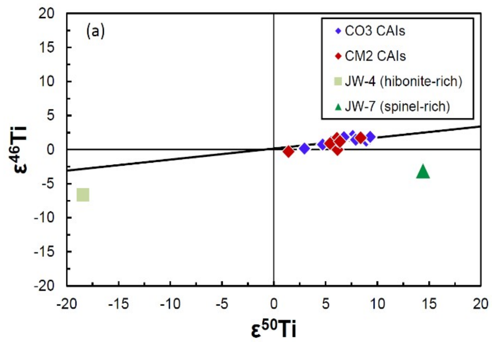

Figure 2: (a) An expanded version of Figure 1, showing the irregular Ti isotopic signatures of JW-4 and JW-7.

Discussion: The regular CO and CM CAIs investigated in this study exhibit a range of Ti isotopic compositions that is indistinguishable to those previously reported for CV [8] and CK [9] CAIs. In addition, all regular CAIs investigated to this point plot on or close to a single linear correlation in ε^{46}Ti vs. ε^{50}Ti space, which has been attributed to the heterogeneous distribution of anomalous Ti carrier phase(s) in the CAI-forming region [8]. These coinciding signatures point towards a close genetic relationship of refractory inclusions found in CV, CK, CO, and CM chondrite groups, revealing that these inclusions were formed from similar material. The reason for the outstanding Ti isotope signature of the sample JW-6 is currently unknown, however, this CAI is additionally interesting with regards to its calcite-rich mineralogy, suggesting it has been subject to a rather uncommon history for CAIs.

Collectively, the nucleosynthetic conformity in Ti isotopes among CAIs from different groups of carbonaceous chondrites indicates a shared genetic heritage. In addition, CAIs from ordinary chondrites show similar enrichments in ^{50}Ti [10], indicating that inclusions in non-carbonaceous chondrites are similarly related. Moreover, these coinciding nucleosynthetic signatures are in good agreement with previous studies that demonstrate a ^{16}O-rich nature [*e.g.*, 11-13] and canonical $(^{26}Al/^{27}Al)_0$ [*e.g.*, 13-14] in such CAIs throughout different chondrite classes and groups. Combined, these isotope data demonstrate that regular CAIs, regardless of their host meteorite, sampled a similar mixture of matter, most likely reflecting the fact that they derived from a single CAI-forming region.

The presence of closely affiliated refractory inclusions throughout various chondrite groups—each representing a discrete accretion region of variable distance from the Sun [*e.g.*, 15]—provides evidence for efficient and large-scale transport processes prior to cementation of the CV, CK, CO, CM parent bodies. Such extensive early Solar System dynamics could also explain the presence of micrometer-sized CAI-like particles in samples of the comet 81P/Wild 2 [16], which is thought to have accreted beyond the ice line at a heliocentric distance >10AU [17].

In contrast to the isotopic similarities of regular CAIs, the two hibonite-rich samples JW-4 and JW-7 exhibit highly anomalous and irregular nucleosynthetic Ti isotopic signatures. Neither inclusion fits the ε^{46}Ti-ε^{50}Ti-correlation defined by regular CAIs (Figure 2) and both exhibit large isotopic anomalies in ε^{48}Ti (12.9 and –11.7, respectively), where regular CAIs show no or barely resolved nucleosynthetic isotope anomalies [8, this study]. As such, JW-4 and JW-7 must have sampled disparate material from regular CAIs, either due to spatial or temporal differences. Intriguingly, it has previously been argued that hibonite-rich grains could have similarly formed from a far less equilibrated reservoir [2], prior to regular CAIs and before ^{26}Al arrived in the protoplanetary disk (Figure 3).

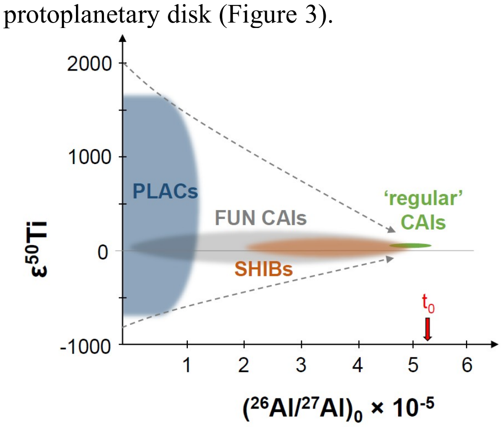

Figure 3: Relationship between ε^{50}Ti and inferred initial $(^{26}Al/^{27}Al)$ in a variety of refractory materials (t_0 = canonical [14]).

Unfortunately, due to the lack of high-precision Ti isotope data of single PLACs and or SHIBs, it is currently not possible to confirm or exclude genetic links of JW-4 and/or JW-7 to either hibonite-rich grain type. Nevertheless, given their extraordinary characteristics, these inclusions may similarly represent an earlier generation of refractory matter and may bridge the compositional and temporal gap from hibonite-rich grains to regular CAIs.

References: [1] Dauphas and Schauble (2016) *Annu. Rev. Earth Planet. Sci.* 44, 709. [2] Kööp et al. (2016) *GCA* 189, 70. [3] Kööp et al. (2017) *GCA* 221, 296. [4] Liu et al. (2009) *GCA* 73, 5051. [5] Charlier et al. (2006) *Chem. Geol.* 232, 114. [6] Zhang et al. (2012) *Nat. Geosc.* 5, 251. [7] Gerber et al. (2017) *ApJ* 841, L17. [8] Davis et al. (2018) *GCA* 221, 275. [9] Torrano et al. (2017) *LPSC 48*, #3045. [10] Ebert et al., (2018) *EPSL* 498, 257. [11] McKeegan et al. (1998) *Science* 280, 414. [12] Matzel et al. (2013) *LPSC 44*, #2632. [13] Ushikubo et al. (2017) *GCA* 201, 103. [14] Jacobsen et al. (2008) *EPSL* 272, 353. [15] Desch et al. (2017) arXiv: 1710.03809. [16] Simon et al. (2008) *MAPS* 43, 1861. [17] Brownlee et al. (2006) *Science* 314, 1711.