TOWARDS UNDERSTANDING THE SOURCE OF NUCLEOSYNTHETIC ANOMALIES IN REFRACTORY INCLUSIONS, G.A. Brennecka1, C. Burkhardt1, T.S. Kruijer1,2, T. Kleine1 1Institut für Planetologie, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (*brencka@gmail.com) 2Lawrence Livermore National Laboratory.

Introduction: Calcium-aluminum-rich inclusions (CAIs) represent the starting point of the Solar System, and yet they have been known for decades to exhibit non-mass dependent isotopic anomalies in elements like O, Cr, and Ti that are disparate from other later-formed Solar System materials [e.g., 1-3]. The range of elements showing isotopic differences between CAIs and other Solar System material has recently been extended by numerous groups to virtually the entire periodic table [see review by 4]; however, the source(s) of these isotopic anomalies in CAIs—and by extension, the difference in the source material of CAIs and later-formed solids—has yet to be identified.

Compared to terrestrial standards, CAIs contain anomalies that appear to scale with the mass of the element measured, and require both excesses and deficits of a given nucleosynthetic component for the exact same sample [5]. Also, intriguingly, the character of the isotopic anomalies (i.e., p-, s-, or r-process excesses or deficits) also appears to be a function of the element measured [5-7], although there has so far been little integrated data involving elements that can easily distinguish between s- and r-process nucleosynthetic patterns, such as Mo. Thus, in order to better understand the possible sources and isotopic character of nucleosynthetic anomalies in CAIs, in this work we study a number of previously investigated CAIs from [6] and [7] with reported isotopic heterogeneity in Mo and W, both fine- and coarse-grained, for a number of different elements.

Samples & Methods: CAIs from [6] and [7], which previously reported variable isotopic signatures in the siderophile elements Mo and W, were the targets of further isotopic investigation of lithophile elements. The CAIs studied were primarily from Allende (N=13), but also included one CAI from NWA 6870 and one CAI from NWA 6717, all CV3 meteorites.

All elements were isolated using ion exchange chemistry using previously established methods (Ti [8], Sr, Ba [5], and Mo [6]). Isotopic compositions of Ti and Mo were measured on a NeptunePlus MC-ICPMS; Sr and Ba were measured on a TritonPlus TIMS, both located in the Institut für Planetologie in Münster.

Results & Observations: Relative to Earth, all CAIs in this study exhibit distinct isotopic anomalies in all systems measured (Ti, Sr, Ba, and if not previously reported, Mo). The most revealing isotope for each element is shown in Fig. 1.

Figure 1 – The integrated isotopic results for Ti, Sr, Ba, and Mo from this work. Previous data on the same samples are plotted for Mo [6] and W [7]. Anomalies are shown in ε-notation, or parts per 10,000.

For the lithophile elements Ti, Sr, and Ba, the results obtained here are neither unique nor surprising. Broadly, these new data simply corroborate previous work showing that CAIs—regardless of type or condensation history—have distinct but relatively consistent nucleosynthetic anomalies. Slight variations are undoubtedly present in some of these elements, with some variations more pronounced in certain elements than others. The sources of these slight variations can and should be debated, though when viewed holistically, the lithophile elements in CAIs generally have a reproducible nucleosynthetic anomaly for each given element that appears to scale with the mass of the element [5].

However, the broad isotopic consistency in lithophile elements is only shared in the isotopic signatures of the siderophile elements Mo and W in coarse-grained CAIs, which seem to have a relatively homogenous isotopic composition for both Mo and W. In contrast, fine-grained CAIs show much larger and more variable isotope anomalies in both Mo and W. Additionally, compared to terrestrial standards, the isotopic character of coarse-grained CAIs is represented by an excess in r-process material, whereas fine-grained samples exhibit a range of excesses and deficits in s-process derived material. The isotopic patterns for Mo in samples of this study are shown in Fig. 2.
Discussion: One of the critical observations from this data set is that coarse-grained CAIs have \( r \)-process excesses in Mo and fine-grained CAIs have both \( s \)-process excesses and deficits. This implies that coarse- and fine-grained CAIs have a fundamentally different genetic fingerprint and derive from fundamentally different nucleosynthetic sources. Taken at face value, this genetic difference excludes the possibility that coarse-grained CAIs formed from melted and recrystallized fine-grained CAI-precursors, as previously suggested by Al-Mg systematics [9].

Additionally, since the Mo isotope anomalies found in fine-grained CAIs are not correlated with W anomalies [7] in the same samples, there must be multiple carriers of Mo and W anomalies from isotopically distinct regions that were enriched (or depleted) with different types of stellar materials.

The source of anomalies in CAIs? It appears that from this and previous studies, the bulk of lithophile elements have a relatively homogenous isotopic signature in CAIs that is distinct from terrestrial rocks. Thus, the most straightforward explanation is that CAIs simply formed in an isotopically different reservoir than later-formed solids [6]. However, since siderophile elements like Mo and W exhibit variable, and decoupled, isotopic signatures in the same samples, the sources of Mo and W anomalies likely come from distinct phases within the CAIs, at least for fine-grained samples.

The most likely hosts for Mo and W in CAIs—and therefore a likely candidate for the source of the isotopic anomalies—are refractory metal nuggets (RMNs). However, these ultra-refractory sinks of siderophile elements are rarely present in fine-grained CAIs, whereas RMNs are the primary host phase for refractory metals in coarse-grained CAIs [10]. Since the concentration of RMNs and refractory metals is generally much higher in coarse-grained CAIs, RMNs are likely not the source of the isotopic anomalies seen in fine-grained inclusions.

Interestingly, Mo isotope anomalies measured for chemical separates of the Murchison CM2 meteorite [11], along with physical chondrule and matrix separates from Allende [12] define virtually identical \( s \)-process mixing lines as the fine-grained CAIs of this work. This isotopic relationship strongly implies that the Mo hosted in all of these phases shares a common ancestry, and one that is notably different from that of coarse-grained samples with an \( r \)-process signature. If the source of the Mo for fine-grained CAIs is genetically linked to that of samples on the “carbonaceous chondrite” line [12], this suggests that the source of Mo in fine-grained CAIs is similar to that of later-formed phases such as chondrules and matrix materials. This would therefore imply that the \( r \)-process signatures of coarse-grained CAIs may represent a more primitive signature for Mo and W, one that is unseen in later-formed meteoric components.