TITANIUM ISOTOPE ANOMALIES IN CM HIBONITES: NUCLEOSYNTHETIC SOURCES AND MIXING IN THE EARLY SOLAR SYSTEM
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Introduction: The Solar System formed from a variety of different nucleosynthetic sources, however, the mechanism and the timing of mixing and identities of these sources remain points of debate. Isotope anomalies have been observed in various early Solar System materials including chondrites, achondrites and chondritic components. These anomalies are evidence of mixing of material with differing nucleosynthetic histories produced in various stellar environments showing that, while extensive, mixing in the early Solar System was not complete. The magnitude of observed isotope anomalies varies significantly between different meteorite groups and meteoritic components, as well as between different elements. While it is likely mixing was in fact between many different pre-solar sources, several elements show evidence for binary mixing in bulk meteorites, e.g. Ni, Ti [1, 2]. However, the isotopic compositions of some meteoritic components, e.g. the FUN (fractionated with unknown nuclear effects) calcium, aluminium rich inclusions (CAIs), are not compatible with binary mixing, so may have experienced different mixing processes or may sample more sources. This variation in the magnitude of anomalies contains information about the composition and identity of the nucleosynthetic sources, the bulk composition of the pre-pollution proto-solar nebula and the processes by which these different reservoirs were mixed. Investigation of highly variable samples such as FUN CAIs may lead to a better understanding of mixing processes and the distribution of sources in the proto-Solar nebula.

One population of meteoritic components, the hibonite grains, stands out as being of particular interest. Hibonite is a highly refractory mineral and was one of the first minerals to form in the Solar System either as a condensate or a refractory residue, for a detailed discussion of hibonites see [3]. Some Hibonite grains from CM chondrites show among the largest isotope anomalies in Solar System materials [4] while others contain canonical levels of ^{26}Al. This high level of ^{26}Al shows that at least some hibonites likely formed contemporaneously with the normal population of CAIs, making them some of the earliest minerals to form within the Solar System. Other grains, however, contain either supra-canonical or essentially no ^{26}Al, the latter suggesting possible a link with the FUN CAIs, showing that hibonite may have formed over a long timescale or in a highly heterogeneous environment.

Titanium is a major element in hibonite and has five stable isotopes which are produced in different proportions by different nucleosynthetic conditions. Therefore, Ti offers a good opportunity to investigate the nucleosynthetic sources of hibonites and to trace mixing of nucleosynthetic sources between different regions of the early Solar System. Anomalies in Ti isotopes have been observed in both the normal [5] and FUN [6] CAI populations. Anomalies were subsequently identified in other meteoritic components and bulk meteorites [7, 2]. The most extreme compositions, however, were observed in the platy hibonite population from CM carbonaceous chondrite (CC) [4], and are among the largest isotope anomalies of any element in grains that formed within the Solar System.

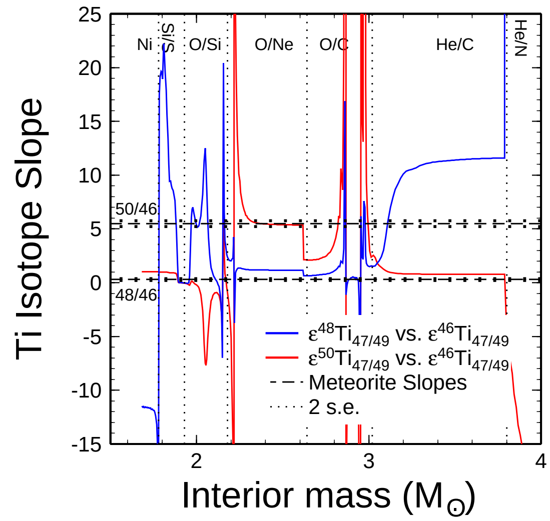

Figure 1: The slope in internally normalised Ti isotope space produced by mixing small fraction of individual shells of a 15 $M_\odot$ SN II (modelled by [8]) into the Solar System composition, see [1] for details. Also shown are the zones names after [9].

Discussion: Several studies, including [10, 11, 4], have attempted to fit the hibonite Ti isotope data (and in some cases other meteoritic samples) in three internally normalised ratio space to a best fit plane and concluded that at least four distinct nucleosynthetic components are required to describe the distribution of compositions. Trinquier et al. [2], however, found a positive correlation between $\varepsilon^{50}Ti_{\frac{49}{47}}$ and $\varepsilon^{46}Ti_{\frac{49}{47}}$ in bulk meteorites and normal CAIs. This positive correlation shows that the Ti isotope compositions of bulk meteorites and CAIs can be explained by mixing of three or fewer components, while the very limited variation in $\varepsilon^{48}Ti_{\frac{49}{47}}$ suggests it may be possible that Ti isotope variation in bulk meteorites can be explained by binary mix-

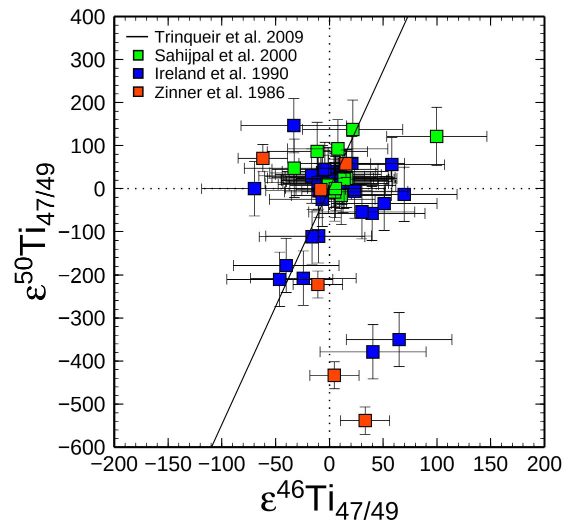

Figure 2: Figure showing hibonite data from previous studies [13, 4, 14, 2]. The data have been recast to use the $^{47}Ti/^{49}Ti$ as the normalising ratio. Uncertainties were estimated using a monte-carlo simulation based the external precision for each individual study. Also shown an extrapolation of the slopes observed by [2]. For clarity, the scale has been reduced meaning the most extreme samples are not shown, note these most extreme data do not fall on the bulk meteorite correlation

ing alone. The bulk meteorites may be sampling only one of the multiple components present in the inclusion populations.

The isotopes ^{50}Ti and ^{46}Ti were not thought to be produced in the same nucleosynthetic environment which led Trinquier et al. [2] to suggest a mechanistic reason for the correlation observed in bulk meteorites. However, by allowing for anomalies on all the isotopes, Steele et al. [1] and Qin et al. [12] showed that the correlation in Ti isotopes observed in bulk meteorites was consistent with input from the O/Ne zone of an SN II ($\sim$15 $M_\odot$), see figure 1. Figure 1 shows the variation slope in Ti isotope space produced by mixing a small amount of each shell from a 15 $M_\odot$ SN II into the bulk Solar System composition. This low mass SN II produces a much better fit than found by [1] suggesting that the source of the anomalous component observed [2] may in fact produced by a low mass SN II.

Interestingly, some of the FUN population of CAIs, typified by the inclusion C-1 [15], also exhibit Ti compositions compatible with the anomalies observed in bulk samples by [2]. Indeed, Niederer et al. [15] also measured the 'absolute' Ti isotope ratio and found the largest anomalies reside on ^{50}Ti and ^{46}Ti supporting the assertion of Trinquier et al. [2] that the anomalies reside on these isotopes alone and are not due to partial contributions from the normalising ratio. Moreover, Steele et al. [1] suggested there is a hint from hibonite data in previous studies [13, 4, 14] that the same source may be present in the hibonite inclusion population. Figure 2 shows a more comprehensive compilation of data from previous hibonite studies than used by Steele et al. [1], the data have been re-normalised to use $^{47}Ti/^{49}Ti$ as the normalising ratio. This figure show that some of the hibonite grains have a composition that falls on an extrapolation of the array observed by Trinquier et al. [2] in bulk meteorites and normal population of CAIs. This suggests that a subset of the hibonite population, in addition to bulk meteorites normal CAIs and C-1 type FUN CAIs, is sampling the same anomalous component which may have been produced in the O-Ne zone of a low mass SN II.

The different meteoritic materials which exhibit this anomalous source represent different environments and sample the early Solar System at different scales and times. The bulk meteorites represent a large-scale graded variation in pre-Solar signatures between different parent body forming regions, while the various inclusions represent sampling of a specific formation environment both spatially and temporally removed from the bulk meteorites. For example, the CAIs formed very early in the evolution of the early Solar System, probably close to the proto-Sun, whereas the meteorite parent bodies formed during a much longer time period and over several AU. It is intriguing that, for some elements, the bulk meteorites sample only one of the numerous sources observed in hibonites and FUN CAIs. This could be explained if the carrier phase, possibly formed in the O-Ne zone of a low mass SN II, is chemically or physically susceptible to both sampling by the various inclusion populations and heterogeneous distribution between the different meteorite parent body forming regions. Another possibility is that one of the inclusion populations, most likely the hibonite grains, is the carrier phase of Ti isotope variations in bulk meteorites and the normal population of CAIs. New, higher precision Ti isotope data in hibonite grains will yield greater insight into the sources of Ti isotope variation in meteoritic materials and mechanisms by which these sources were mixed.

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