ARE $^{48}$CA ANOMALIES ENDEMIC OR UBIQUITOUS IN ALLENDE CAI'S?

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Measurements in our laboratory [see 1,2] and elsewhere [3,4] of Ti and Ni isotopic abundances in Ca-Al-rich inclusions (CAI's) from the Allende meteorite have shown that isotopic anomalies exist in virtually all CAI's studied. However, the anomalies appear to be restricted to Ti which makes it difficult to assess the nucleosynthetic processes which may be responsible for their production. The dominant excesses in $^{50}$Ti can be produced, for example, by neutron rich equilibrium or neutron-rich Si-burning [5], but various other neutron-rich nuclei in the same mass region are expected to be coproduced by these mechanisms. As was discussed in [2] the lack of resolvable anomalies in Ni suggests that n-rich Si-burning may be the preferable process because nuclei of elements heavier than Ti are not expected to be generated in such an environment. But it may simply be the result of physico-chemical processes related to the difference in volatility of the two elements. In any case, coproduction of $^{48}$Ca is expected to occur while, at the same time, overproduction of $^{48}$Ca would be avoided. High precision data on Ca isotopic abundances in CAI's from Allende have been reported previously in several papers by the Caltech group. Their results indicate that, although mass dependent isotope fractionation effects are widespread and variable, non-linear isotopic effects are extremely rare and appear to be restricted to a small group of CAI's called FUN inclusions [6]. In order to gain further constraints on possible nucleosynthetic processes and increase the data base, we developed procedures for the high precision analysis of Ca isotopic abundances in our laboratory.

All samples selected for our first Ca measurements were solutions of CAI's from which Ti and Ni isotopic abundances had been obtained previously. The clean extraction of Ca required a slight modification of our established chemical procedures. In particular, sufficient separation of traces of Ti is imperative since Ti would interfere with the heavy Ca isotopes during mass spectrometric analysis. Ca was loaded on V-shaped Ta filaments containing a bed of high purity fine grained Ta$_2$O$_5$ powder. With typical sample amounts of 2 to 4 $\mu$g stable ion currents of $\sim$6$\times$10$^{-11}$ A could be maintained for more than 17 hours. The Ca spectra were carefully monitored for cleanliness and isobaric interferences; specifically, the main isotope of Ti would interfere with $^{48}$Ca. Since the emission of TiO ions is consistently $\sim$20$\times$ higher than Ti$^{+}$ we monitored Ti as TiO$^+$. The contribution of $^{48}$Ti to $^{48}$Ca was always below 0.2 $\epsilon$-units and therefore negligible.

The results are presented in Fig. 1 as relative deviations ($1\epsilon = 1$ part in 10$^5$) from the normal. A solution made from high purity CaCO$_3$ was used as the isotope standard. For the sample sizes used we observed a variation in mass dependent fractionation during a run of typically 8 $\epsilon$/amu. We noted, however, that our mean uncorrected value for $^{44}$Ca/$^{40}$Ca was consistently $\sim$2.3$\times$ higher than the value used by the Caltech group for fractionation correction. In order to minimize the correction for mass dependent fractionation, particularly on $^{48}$Ca/$^{40}$Ca, we decided to use a value of $^{44}$Ca/$^{40}$Ca = 0.0217. The fractionation law applied by us is similar to the exponential law discussed by Russel et al. [7].

In Fig. 1 we present the results for nine samples: six coarse and three fine grained inclusions. All samples were measured repeatedly to allow resolution of deviations from the normal larger than 2.5 $\epsilon$ units at the 95% confidence level on $^{48}$Ca. It is obvious from this figure that the values for $^{42-46}$Ca/$^{40}$Ca all agree with the normal within precision. $^{48}$Ca/$^{40}$Ca, however, exhibits variations ranging from 0 to $\pm 6 \epsilon$-units. In this limited database 7 out of 9 samples show clearly resolved excesses on $^{48}$Ca. This is a striking result which was not expected from previously published data. From this diagram no systematic trend is discernible; the magnitude of anomalies is the same for coarse and fine grained inclusions and each group includes one sample with normal $^{48}$Ca/$^{40}$Ca. However, there are three coarse grained CAI's which were shown to have fractionated (F) Mg [8,9], including one with documented mass dependent fractionation in Ca [8], which therefore, could be members of the FUN family. There may be an indication that the normal coarse CAI's have lower excesses on $^{48}$Ca. But two fine grained samples, which showed normal isotopic patterns in several elements, exhibit excesses similar to those of the possible FUN CAI's. Still, it appears that isotopic variations on $^{48}$Ca are quite common.

An important question is whether these Ca isotope anomalies are in any way related to the omnipresent Ti anomalies, as would be expected for specific nucleosynthetic processes. In Fig. 2 the $^{48}$Ca anomalies are plotted as a function of the corresponding $^{50}$Ti excesses. The insert in Fig. 2 provides a comparison of the Ca and Ti results from the two major FUN inclusions EK 1-4-1 and C1 [10,3] with those obtained in our laboratory and demonstrates the difference in magnitude of the currently observed effects. In general, no simple correlation can be observed. The $^{48}$Ca isotope variations appear to be independent of those in $^{50}$Ti. While for the coarse grained CAI's $^{50}$Ti excesses exhibit a narrow relative range, $^{48}$Ca varies from 0 to $\pm 6 \epsilon$ units. In contrast, with a similar variation in Ca, $^{50}$Ti in the fine grained inclusions varies by a factor of two. With the extreme excess in 7R-41 of 28 $\epsilon$ units in $^{50}$Ti there may be a hint of an inverse correlation among the fine grained inclusions (dashed line in Fig. 2). However, given the limited data, we consider it premature to attach significance to this trend. In any case, if the anomalous $^{48}$Ca and $^{50}$Ti components were indeed coproduced by the same process it is clear that later
events (vaporization, metamorphism, etc.) must have affected Ca to a higher degree than the more refractory Ti. This scenario would also be consistent with the lack of Ni isotopic anomalies [2]. On the other hand, a partial decoupling of the production of the n-rich Ca and Ti isotopes can not be excluded. In conclusion, we have shown that within our limited data base isotopic anomalies on $^{48}\text{Ca}$ are common but their relationship to the $^{50}\text{Ti}$ excesses is not yet clear.


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Fig. 1: Relative deviations from the normal (in parts in $10^4$) of Ca isotopic data from Allende CAI's. (N) denotes number of repeat measurements of a single sample; (F) samples with mass dependent Mg isotope fractionation [8,9]. Uncertainties are best estimates at the 95% confidence level.

Fig. 2: Relative deviations from the normal of $^{50}\text{Ti}$ vs $^{48}\text{Ca}$ from coarse and fine grained CAI's from Allende. The inset compares the results from the two major FUN inclusions EK 1-4-1 and C1 [10,3] with those obtained in this study (hatched field) and shows the difference in magnitude of observed effects.