# Titanium Isotopes in CAIs - Heterogeneities in the early solar system.

I. Leya[1], M. Schönbächler[2], and A.N. Halliday[3], [1]Physical Institute, University of Bern, Switzerland, [2]School of Earth, Atmospheric and Environmental Sciences, University of Manchester, UK, [3]Department of Earth Sciences, University of Oxford, UK, (Ingo.Leya@space.unibe.ch)

## Introduction

Calcium-rich-Aluminum-rich refractory inclusions are considered to be the first objects yet identified that formed in the solar system. It is now established that most (but not all) of them contain nucleosynthetic anomalies from e-, p-, r-, and/or s-processes. Exactly how and when these heterogeneities in the dust that formed the solar system were established is not yet clear. For a better understanding of the origin of isotope heterogeneities in early solar system objects, studies of correlated anomalies are of great importance. As an example, it has been demonstrated for CAIs from Allende and Efremovka that excesses of the n-rich isotopes $^{62}$Ni and $^{96}$Zr are correlated [1]. In the same study the authors also found correlated $^{62}$Ni and $^{60}$Fe anomalies, suggesting that the n-rich stellar event not only delivered $^{62}$Ni and $^{96}$Zr but also some of the short-lived radionuclides. If true, this would yield useful informations about the timing of the events leading to the formation of the solar system. Here we report Ti isotope data for the same CAIs measured already for Ni [1] and Zr isotopes [2].

## Experimental

We studied five CAIs from the reduced CV3 chondrite Allende (USNM 4698, 3529-21, 3529-41, 3529-44, 3529-47) and two CAIs from the oxidised CV3 chondrite Efremovka (E49, E60). Sample preparation and chemical separation followed the procedure described by [3, 4]. Briefly, Ti was separated via a two-stage exchange chromatography and the Ti isotope ratios were measured using the high resolution MC-ICPMS (NU1700) at the ETH Zürich. Instrumental mass fractionation is internally corrected via $^{49}$Ti/$^{47}$Ti = 0.749766 [5] using the exponential law. The long-term reproducibility ($2\sigma$) for $^{50}$Ti/$^{47}$Ti, $^{48}$Ti/$^{47}$Ti, and $^{46}$Ti/$^{47}$Ti are $0.28\epsilon$, $0.34\epsilon$, and $0.28\epsilon$, respectively [3].

## Results

The Ti isotope data, i.e., $\epsilon(^{50}$Ti/$^{47}$Ti), $\epsilon(^{48}$Ti/$^{47}$Ti), and $\epsilon(^{46}$Ti/$^{47}$Ti) are shown in Fig. 1. Also shown are the results from earlier studies [5, 6, 7] after renormalisation, i.e. normalising the literature data also to $^{47}$Ti and assuming for them also $^{49}$Ti/$^{47}$Ti to be normal (as we do for our data). In addition, we also show the Ti isotope composition for Allende bulk material [3, 4].

Figure 1 illustrates that all inclusions display $\epsilon(^{50}$Ti/$^{47}$Ti) values that are positive by up to $13\epsilon$. However, in contrast to the earlier data, which all scatter around $10\epsilon$ and thus indicate a rather constant $^{50}$Ti/$^{47}$Ti for all CAIs, our new high-precision data show variations between $\sim 2\epsilon$ and $\sim 10\epsilon$ for Allende CAIs. For Efremovka only one inclusion could be measured, E49 gave a $^{50}$Ti excess of $\sim 10\epsilon$.

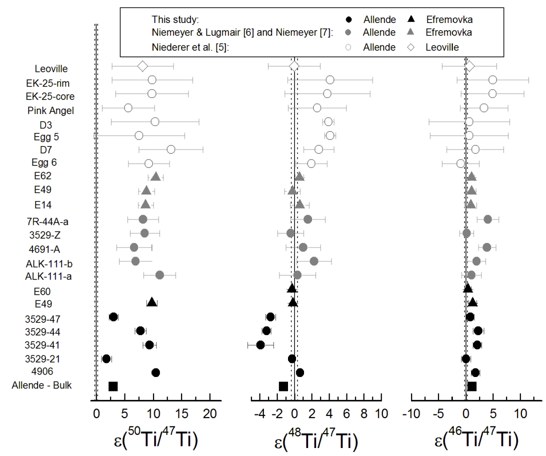


Figure 1: Ti isotopic data, i.e. $\epsilon(^{50}$Ti/$^{47}$Ti), $\epsilon(^{48}$Ti/$^{47}$Ti), and $\epsilon(^{46}$Ti/$^{47}$Ti) for CAIs from Allende and Efremovka. Also shown are literature data [5, 6, 7] (after renormalisation, grey and open symbols) and the Ti isotope composition for Allende bulk material (solid black square) [3, 4].

The CAI data for $^{46}$Ti/$^{47}$Ti show no variation from a normal distribution, indicating no significant variability within the dataset. A statistical test indicates that the datasets for CAIs and terrestrial standards, i.e. synthetic standard solutions and terrestrial rocks, are different at the 97% level, clearly indicating that CAIs are enriched in $^{46}$Ti/$^{47}$Ti by $\sim 1\epsilon$ relative to the normal, defined by ordinary chondrites, eucrites, mesosiderites, ureilites, Earth, Moon, and Mars. Comparing the CAI data to carbonaceous chondrite bulk data [3, 4] indicates that both types of material share the same Ti isotope composition at the 99% level.

The CAI data for $^{48}$Ti/$^{47}$Ti show, compared to the reproducibility of our measurements, a relatively large scatter and therefore probably indicate some inherent heterogeneity. Note that such heterogeneities have also been observed for this ratio in bulk samples of carbonaceous chondrites [3,4]. However, if we nevertheless discuss average values we find that the CAI data differ from normal, i.e. synthetic standard solutions and terrestrial rocks, at the 90% significance level. In contrast, comparing the CAI data to our recent results for bulk carbonaceous chondrites [3,4] indicates that both data sets are identical at the 95% level.

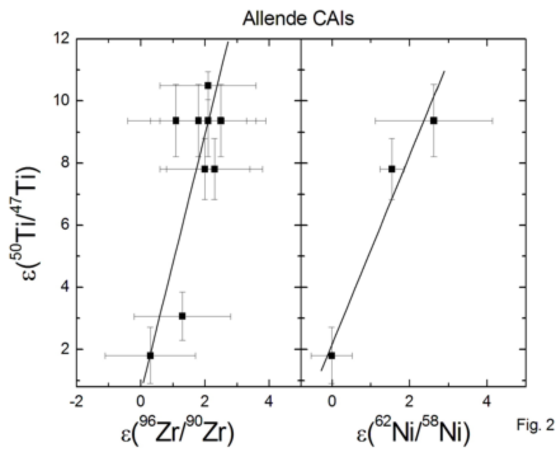


Figure 2: $\epsilon(^{50}Ti/^{47}Ti)$ vs. $\epsilon(^{96}Zr/^{90}Zr)$ (panel a) and $\epsilon(^{50}Ti/^{47}Ti)$ vs. $\epsilon(^{62}Ni/^{58}Ni)$ (panel b) for Allende CAIs. The $^{50}Ti$, $^{62}Ni$, and $^{96}Zr$ excesses tend to correlate, even if only a limited set of data is available. The Ni and Zr data were obtained by [1,2] on aliquots of the same samples, respectively.

In Figure 2a we compare our $^{50}Ti/^{47}Ti$ data with results for Zr isotopes obtained in aliquots of the same samples [2] (except for the Efremovka inclusion). The $^{96}Zr/^{90}Zr$ ratios tend to correlate with the $^{50}Ti/^{47}Ti$ anomalies, even if only a limited set of data is currently available. The linear regression ($r\sim0.88$) gives an offset of $\epsilon(^{50}Ti/^{47}Ti) = 0.61\pm1.25$, which can be interpreted as the initial ratio for material without any nucleosynthetic anomalies in Zr, i.e. for material with $\epsilon(^{96}Zr/^{90}Zr)=0$. The data therefore indicate that primitive solar system material without excess $^{96}Zr$ nevertheless have excess $^{50}Ti$. This finding is confirmed by the bulk data for carbonaceous chondrites. While we measured $\epsilon(^{50}Ti/^{47}Ti) = 3.02\pm0.5$ [3,4], no excess $^{96}Zr$ have been found [8,9]. Note that the slope of the correlation of about 3.5 is in good agreement with the result given by [12]. The $^{50}Ti/^{47}Ti$ data also linearly correlate with $^{60}Ni/^{62}Ni$ ratios measured in aliquots of some inclusions [1], samples high in $^{50}Ti/^{47}Ti$ are also high in $^{62}Ni/^{60}Ni$ and inclusion CAI 3529-21, which is low in $^{50}Ti/^{47}Ti$, also shows normal $^{62}Ni/^{58}Ni$ (Fig. 2b). For this correlation (r = 0.97) we calculate an offset of $2.15\pm1.05$. Therefore, the data indicate that material with normal $^{62}Ni/^{58}Ni$ ratios display a slight excess of $^{50}Ti$ by a few $\epsilon$-units.

To summarize, our new high precision data indicate that the excesses in $^{50}Ti$, $^{62}Ni$, and $^{96}Zr$ are correlated. However, among the three isotopes, $^{50}Ti$ is special, because even samples without anomalies in $^{62}Ni$ and $^{96}Zr$ have a $^{50}Ti$ excess of a few $\epsilon$-units. This finding is confirmed by bulk measurements for carbonaceous chondrites. While bulk samples are normal in Ni and Zr isotopes [1,8,9] they display a $^{50}Ti$ anomaly of $3.02\pm0.5\epsilon$ [3,4]. Also $^{48}Ti/^{47}Ti$ and $^{46}Ti/^{47}Ti$ ratios in CAIs deviate from normal, as defined by ordinary chondrites, eucrites, mesosiderites, ureilites, Earth, Moon, and Mars, but agree with data obtained for carbonaceous chondrite bulk material texttt[3,4]. Our data therefore indicate that, at least in terms of Ti isotopes, CAIs formed from the same material that formed carbonaceous chondrites. Some inclusions, however, started with an additional excess of up to 8 $\epsilon$-units in $^{50}Ti$ (and excesses in $^{62}Ni$ and $^{96}Zr$). Note that [10] found a linear correlation between $^{50}Ti$ and $^{54}Cr$ among inner solar system solids. Adding this isotope to the list we can conclude that there was a n-rich addition to the solar nebula and that this addition was not homogeneously distributed in the early solar system, at least not in the region where CAIs formed. Our new high precision data also indicate that CAIs started with the same Ti isotope composition as bulk carbonaceous chondrites. Consequently, CAI formation and the accretion of carbonaceous chondrite parent bodies probably occurred in the same region in the early solar system. If true, CAI formation was not limited to regions close to the sun, as, e.g., proposed by the X-wind model [11]. In contrast, our data indicate that CAIs formed in the same solar system region as carbonaceous chondrites, probably indicating that CAI formation was a rather local process.

**References**

[1] Quitté et al. 2007, ApJ, 655, 679; [2] Schönbächler et al. 2003, EPSL, 216, 467; [3] Leya et al. 2007, Internat. J. Mass Spectr., 262, 247; [4] Leya et al. 2008, EPSL, 266, 233; [5] Niederer et al. 1985, GCA, 49, 835; [6] Niemeyer and Lugmair 1981, EPSL, 53, 211; [7] Niemeyer 1988, GCA, 52, 309; [8] Schönbächler et al. 2002, LPSC, 33, 1283; [9] Schönbächler et al. 2004, Analyst, 192, 32; [10] Trinquier et al. 2007, Workshop on Chronology of Meteorites, 4054; [11] Lee et al. 1998, ApJ, 506, 898; [12] Harper et al. 1991, LPSC, 22, 517.