ZIRCONIUM ISOTOPES AS AN ASTROPHYSICAL PROBE OF THE NUCLEOSYNTHETIC SOURCE CONDITIONS OF PRIMITIVE SOLAR SYSTEM 'COMPONENTS'

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Among the various elements analysed in isotopic 'anomaly' studies of primitive refractory CAI, titanium has been found to be a particularly powerful discriminator of isotopically distinct nucleosynthetic components. It is likely that these components are everywhere present in the solar system in the isotopically homogenized mixture of bulk solar system (BSS) material, ---though controversy remains over whether or not the distinctive correlated anomalies in ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{58}Fe, and ^{62,64}Ni, associated with the multi-zone mixing (MZM) nuclear statistical equilibrium (NSE) 'e'- process [1] are due to heterogeneous admixtures of an 'exotic' component, or are the result of mixing ratio polarizations between *s*-, *r*-, and *p*- type nucleosynthetic components [2]. As CAI were formed as a result of severe episodes of nebular/protoplanetary processing at high temperatures at very early times, the survival of distinctive component anomaly signatures in Ti --and of particularly large magnitudes in CAI hibonite-- is most probably due to the refractory character of CAI in general and of the Ti carriers hibonite and perovskite in particular. In order to better characterize the astrophysical sources of the nucleosynthetic components resolved in Ti studies, we have chosen to investigate Zr isotopic systematics in CAI. On the basis of the broad similarity in the chemical behavior of both elements we have made the primary working assumption that Ti and Zr experienced broadly coherent cosmochemical histories throughout their respective transits from nucleosynthetic source regions in stars to mineralogical sitings in CAI. As this assumption seems to have held true to a surprising degree for the correlated e - component anomalies in the more chemically dissimilar elements Ca, Cr, Ni, and Fe [Cf. 3 and references therein] it is apparently well justified for Zr. Zr and Ti are known to be associated in CAI perovskite [4] and hibonite [5] and have nearly equivalent cosmochemical enrichment factors (~ x 30) in the latter phase. Zr solid solution has also

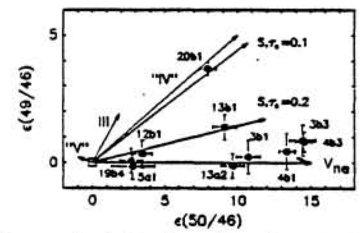
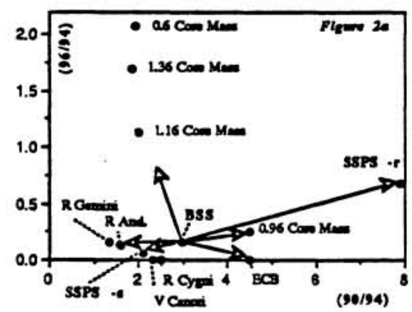
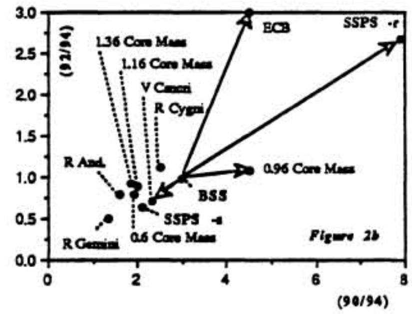
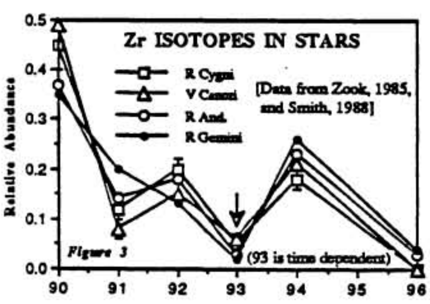


Figure 1. Data from Prombo et al. (companion abstract). V_{ne}, III, IV, and V represent Clayton's, (1981a,b) Ti compositions for NSE, associated supernova shells, and S-components.







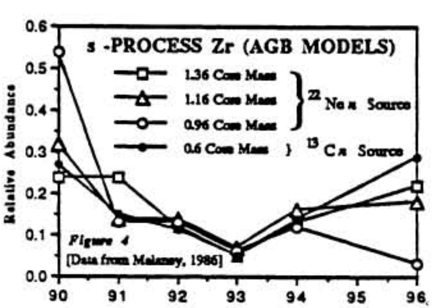
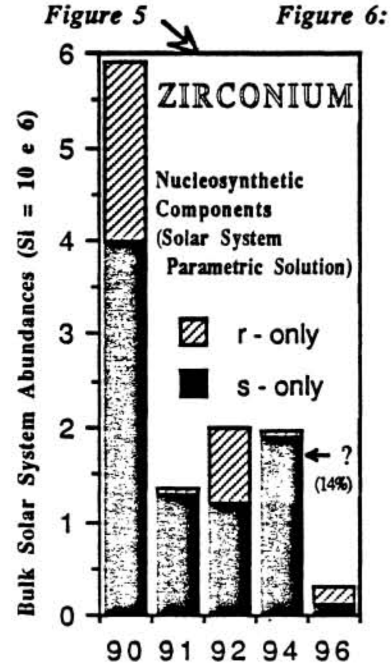
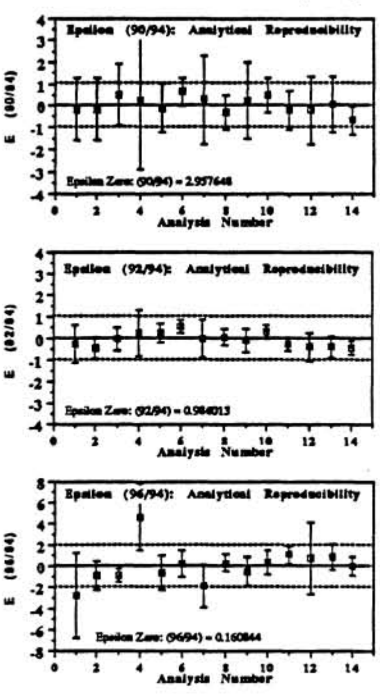


Figure 5 Figure 6:





been observed in (interstellar dust candidate) Ti-oxide 'Magneli phases' extracted from Antarctic ice [6].

Zr Astrophysics: Zr isotopes are particularly interesting from the astrophysical perspective for the following reasons: (i) Optical Zr *isotopic* spectra are obtainable at high dispersion from bandhead splittings of the ionized molecular monoxide present in the cool atmospheres of *s* -processing asymptotic giant branch (AGB) stars [7]. Observational data have been published for 5 stars (4 shown in fig. 3), and have been used to test and refine AGB models of *s* -process nucleosynthesis [8]. (ii) Some Zr isotopic ratios are strong diagnostics of the physical conditions of *s* -processing. In particular the branching at ^{95}Zr allows the ^{96}Zr/^{94}Zr ratio to be used as a sensitive *s* -process neutron densiometer [9]. As the ^{91}Zr/^{94}Zr ratio is a predominantly *s* -only ratio in BSS matter (see fig. 5 [10]), and remains relatively invariant under a variety of different *s* -process conditions, (with respect to ^{90}Zr/^{96}Zr, for example, see fig. 4), it provides a convenient normalization reference for observing isotopic anomalies due to mixing ratio polarizations of both the *s/r/p* type (e.g., Sr, Sm, Nd, Ba [2]) and of s_i -subcomponents derived from different *s* -processing sites (see fig. 2a,b), as have been recently inferred from studies of Kr [11] and Ba [12]. (Anomalies at mass 92 will be interpretatively ambiguous without Nb/Zr measurements and knowledge of the solar system *ab initio* ^{92}Nb/^{93}Nb ratio[13]). (iii) The calculations of [1] for the MZM NSE ***e*** -process do not indicate any anomaly-producing overproduction pattern for Zr. Zr produced in a supernova and co-ejected with MZM ***e*** -Ti might therefore predictably carry a more conventional ***r*** -process signature, thereby allowing new constraints to be derived for the astrophysical conditions of the ***e*** -processing event. Similarly, a correlation between ***r*** -type anomalies in Zr and ***e*** -type anomalies in Ti may be seen as a test of the supernova model for the ***e*** -process. Zr isotopes have also been proposed as a means of identifying products of explosive carbon burning, (ECB), [14].

Ti-Zr Studies of Allende CAI: Ti data generated in this laboratory (see fig. 1, after Prombo *et al.*, companion abstract) are consistent with the existence of one or more *s* -type components in addition to the ***e*** -component. This is apparent from the anomaly plot of ε(49/46) *vs.* ε(50/46) shown in figure 1. Analyses 20b1 and 13b1 lie along mixing vectors representing polarizations towards Clayton's [14] model *s* -components having neutron exposures of 0.1 and 0.2 respectively. However, these data are also consistent with different degrees of mixing between normal Ti, the ***e*** -component, and a ***single*** poorly-defined *s* -component. A similar plot (not shown) of ε(47/46) *vs.* ε(50/46) allows 13b1 to be a mixture of ***e*** - and normal components. As Zr isotopes also allow one to infer the physical characteristics of *s* -processing events, a comparison of *s* -type anomalies in Ti and Zr for same sample analyses may allow better resolution and source characterizations of the Ti-components. Towards this end we have initiated a study of Zr and Ti isotopes in Allende CAI. Results will be reported at LPSC XXI. Here we report (fig. 6) results for a number of analyses of a Zr shelf standard {1-9}, two terrestrial basalts {10,11}, Madagascar hibonite {12}, and Gardar eudialyte {13,14}. Sample quantities ranged from 0.5 to 2.5 μg Zr. The data, (Mo corrected and normalized to ^{91}Zr/^{94}Zr = 0.644700), demonstrate an analytical resolution of ~2ε in ^{90}Zr/^{94}Zr and ^{92}Zr/^{94}Zr, and ~4ε in ^{96}Zr/^{94}Zr. Zr was separated from the terrestrial basalts (50-100ppm) by means of a single cation exchange microcolumn chemistry with yields in excess of 95%. Zr was separated from the eudialyte and hibonite (~90 ppm) by means of the Zr-Hf-specific precipitant *p*- bromomandelic acid, which also gave yields in excess of 95% for ~3 μg Zr with undetectable blanks. CAI compositions, however, do not produce acceptable yields with these methods and require further separation procedures.

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