INTERPRETATION OF THE ^{50}Ti-^{96}Zr ANOMALY CORRELATION IN ALLENDE CAI: NNSE Zr PRODUCTION LIMITS AND S/R/P DECOMPOSITION OF THE BULK SOLAR SYSTEM ZIRCONIUM ABUNDANCES

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^{96}Zr anomalies are correlated with ^{50}Ti anomalies in coarse-grained Allende CAI (fig. 1). Ti anomaly patterns in the 4 inclusions showing positive ^{96}Zr anomalies are identical to those observed in very highly anomalous hibonites [1], and indicate an excess of the neutron-rich nuclear statistical equilibrium (NNSE) "*e* "-component [2], identified by correlated excesses in neutron-rich isotopes of several iron peak elements (Ca, Ti, Cr, Fe, Ni, Zn) in EK1-4-1 [3] and other inclusions [4]. Studies of Ba, Nd, and Sm in EK1-4-1 [5] have also identified positive anomalies at unshielded masses. These are interpreted as *r* -process excesses and parameterized according to an *r* -process excess parameter, η_r. For a mixed source isotope, η_r is related to the abundance anomaly, ε, by: $\varepsilon = \eta_r(N_r/N)$, where N_r/N is the *r* -process abundance fraction. In EK1-4-1, $[\eta_r / \varepsilon(^{50}Ti)] \sim 1$. Hence the *e* - and *r* -process polarizations evident in Ti and REE are approximately equivalent in this inclusion if $\varepsilon(^{50}Ti) \sim \eta_e$, *viz.*, if nearly all ^{50}Ti in the bulk solar system (BSS) mix is an *e* -process product ($N_e/N \sim 1$). We describe the correspondence between positive anomalies in *e* -process isotopes and positive *r* -type anomalies as a 'cosmochemical association' between NNSE and the *r* -process. This association may allow an 'isotopic astronomy' of nucleosynthesis occurring deep within supernovae, though the intervening cosmochemistry leading to the preferential preservation of isotopically anomalous compositions in CAI and hibonites remains very much a mystery at present. In the simplest model, the correlated anomalies in CAI correspond to a spatial correlation of *astrophysical site* within one or more supernovae contributing material into the protosolar reservoir. For example, matter ejected from zone 1 near the mass cut of the type II supernova shown in figure 2 would preferentially find its way into a CAI, relative to its average proportion within the bulk solar system (BSS) mixture, and be expressed as a suite of positive anomalies in NNSE isotopes. A positive *r* -process anomaly association would therefore indicate a zonal association within supernovae of NNSE and the (as yet unidentified [6]) site of the *r* -process. (Indeed, the presence of ^{26}Al, ^{53}Mn, ^{107}Pd and ^{182}Hf (see companion abstract) in the early solar system is consistent with the idea that one or more supernovae did occur near in time and place to the solar system's birth ---perhaps in an OB association?) Alternatively, chemical processes in the ISM and solar nebula acting upon the 'old material' may preferentially associate previously unassociated nucleosynthetic components via interstellar and/or early nebular sorting mechanisms dependent upon physico-chemical similarities in interstellar grain populations ('cosmic chemical memory': CCM), as advocated by Don Clayton.

The interpretation of ^{96}Zr anomalies as *r* -process excesses assumes that NNSE is not their source. NNSE calculations (fig. 4) do show that an "*e* -Zr" is made within the range of neutron excess, η, spanned in the best-fit multi-zone mixing model of [2]: $0.165 < \eta_{max} < 0.175$. However, ^{i}Zr abundances for all η_{max}, (normalized to BSS ^{50}Ti: fig. 5), are <0.1% of the BSS abundances (^{96}Zr is well below 1ppm). NNSE therefore cannot account for the observed mass-96 anomalies.

Zr is predominantly an *s* -process element, and has no shielded isotopes (fig. 6): all masses are mixed source ($N_r/N < 1$). The quantitative interpretation of isotopic anomalies in Zr is therefore dependent upon an accurate decomposition of the BSS abundances into *s* - and *r* - contributions. Recent *p* -process calculations for a Type Ia supernova model [*Cf.*, companion abstract] show significant yields for N = 50 nuclides (and a good fit to the BSS ^{92}Mo abundance), and suggest that a significant fraction of ^{90}Zr in BSS is a *p* -process product (~40%, see table). As ^{96}Zr anomalies are not accompanied by ^{90}Zr anomalies (fig. 3), as expected for an *s* -process deficit (or 'non-*s* ' excess), *p* -^{90}Zr is not cosmochemically associated with the NNSE and *r* -process source: the observed component polarization is: $(e+r)$ *vs.* $(s+p)$. Both the absence of resolvable ^{90}Zr anomalies and the lack of significant BSS residual after subtraction of the *s* - and *p* - fractions, also constrains the α-process scenario of [7], which generates maximal overproductions for ^{90}Zr in certain parameterizations. (In others the most overproduced nuclide is ^{96}Zr !)

Because of the 64d branch at ^{95}Zr (fig. 6), ^{96}Zr is produced in pulsed He shell burning in AGB stars [8]. Indeed, recent calculations [9] have overproduced ^{96}Zr in models constrained to fit the BSS *s* -only distribution. Zr yields are shown in the table for a BSS best fit *s* -process calculation for a low-mass AGB star model, (taking into account known variations of cross-section with temperature). ('Classical model' abundances are those of [8, 10].) The residuals obtained after subtraction of the estimated *p* -process and 'weak' component fractions (from massive stars [11]) are also shown. Uncertainties in the decomposition are probably larger than the residuals for all Zr masses except ^{96}Zr. For ^{96}Zr we obtain a range of *r* -process fractions: $0.15 < N_r/N < 0.32$, for the uncertainty: $50mb < \sigma(^{95}Zr) < 60mb$. The actual range, including additional model uncertainties, will be larger. However, $^{96}Zr/^{94}Zr$ ratios in the range 0.1-0.3 (BSS = 0.16) have been observed in the ZrO^+ spectra of 2 S-stars actively undergoing *s* -processing [12], consistent with our conclusion that the greater fraction of ^{96}Zr in BSS is *s* -process. (^{93}Zr abundances in these stars also indicate that the atmospheric Zr is > 80% *s* -process [13].) For $N_r/N \sim 1/4$, ($N_r = 0.08$), the observed ^{96}Zr anomalies are reproduced for $\varepsilon(^{50}Ti) = \eta_e = \eta_r = +0.10\%$ (fig. 7), (assuming $\eta_e = \eta_r$, as in EK1-4-1). $N_r = 0.08$ for ^{96}Zr is very close to the residuals obtained for ^{97}Mo (0.09) and ^{98}Mo (0.09) by [10], but is substantially less than $N(^{100}Mo) = 0.25$, which is *r* -only. For a flat $N_r = 0.08$ *r* -process abundance distribution, no resolvable anomalies would be present at other Zr masses, consistent with observations. Refs.: [1] C. L. Harper *et al.*, (1990). *Meteoritics*, 25: 369; E. K. Zinner *et al.*, (1986). *Ap. J.*, 311: L103; [2] D. Hartmann *et al.*, (1985). *Ap. J.*, 297: 873; [3] J. Völkening and D. A. Papanastassiou, (1990). *Ap. J.*, 358: L29, and refs therein; [4] R. D. Loss and G. W. Lugmair, (1990). *Ap. J.*, 360: L59, and refs therein; [5] G. W. Lugmair, (1978). *USGS Open-File Rpt.* 78-701, p. 262; G. J. Mathews and W. A. Fowler, (1981). *Ap. J.*, 251: L45, and refs therein; [6] G. J. Mathews and J. J. Cowan, (1990). *Nature*, 345: 491; [7] S. E. Woosley and R. Hoffman, (1991 preprint); [8] K. A. Toukan and F. Käppeler, (1990). *Ap. J.*, 348: 357; [9] F. Käppeler *et al.*, (1990). *Ap. J.*, 354: 630; [10] F. Käppeler *et al.*, (1989). *Rep. Prog. Phys.*, 52: 945; --- (1989 preprint); [11] C. M. Raiteri *et al.*, (1990). In: *SN 1987A and Other Supernovae;* [12] V. V. Smith, (1988). In: G. J. Mathews (ed.) *Origin and Distribution of the Elements*, p. 535; [13] H. Beer and G. Walter, (1984). *Astron. Astrophys.*, 133: 317.

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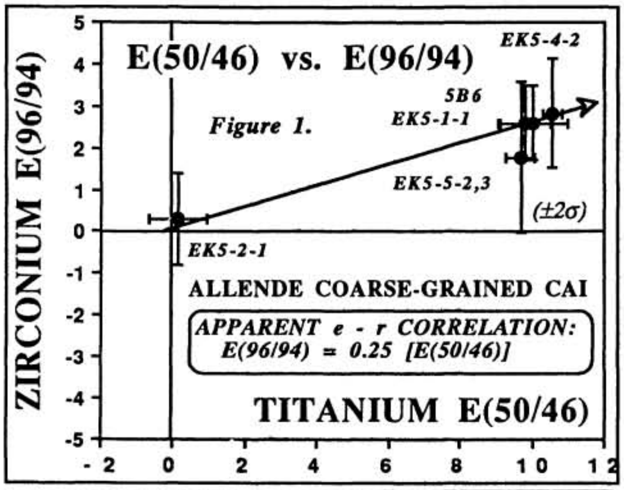
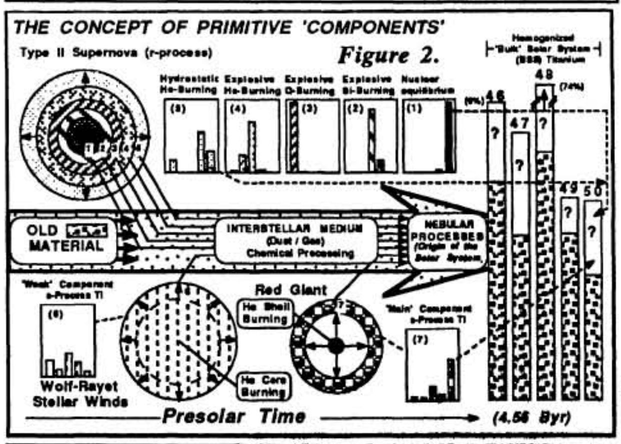


Figure 1.



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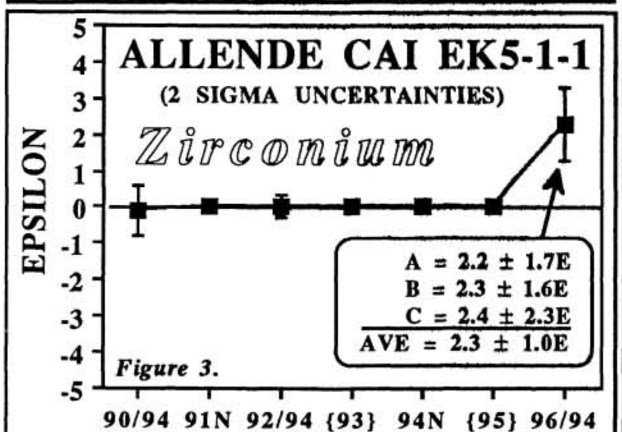

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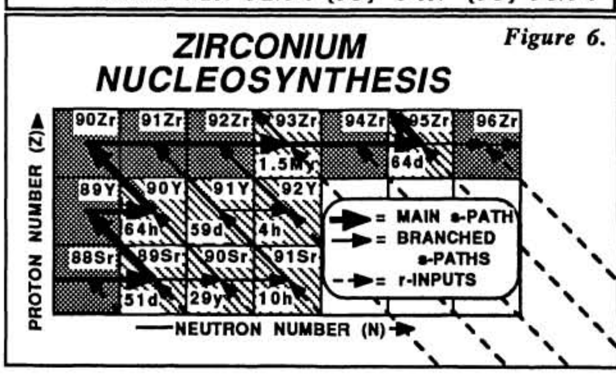

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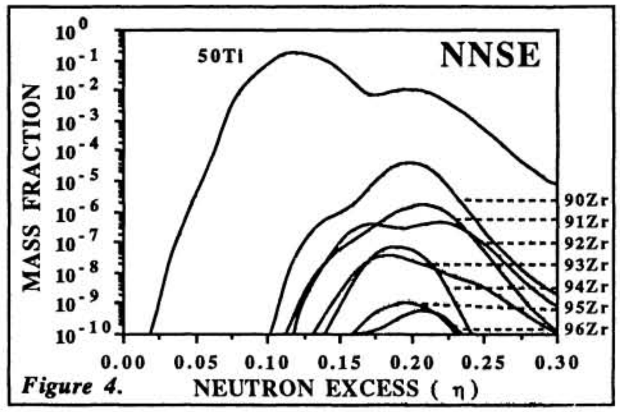

Figure 4.

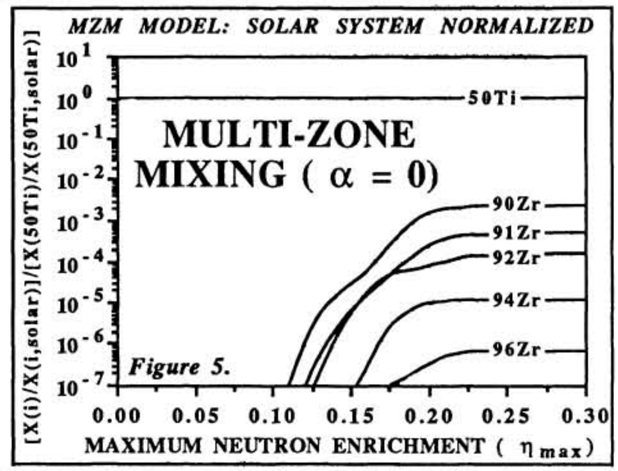

Figure 5.

Table: ***BULK SOLAR SYSTEM (BSS) ZIRCONIUM NUCLEOSYNTHETIC SOURCE DECOMPOSITION***

Abundance (atom #):	^{90}Zr	^{91}Zr	^{92}Zr	(^{93}Nb)	^{94}Zr	^{96}Zr
[N(BSS, Si=10^6):	5.87	1.28	1.96	0.698	1.98	0.32]
(uncertainties in parentheses)						
He-shell burning: *Classical model:*						
(ia) 'Main' s-process:	3.5(.4)	1.16(.2)	1.9(.3)	0.59	1.9(.1)	0.11(.05)
He-core burning: (iia)'Weak' s-process:	-----	-----	-----	-----	-----	-----
Non-s residuals:	2.37(.8)	0.12(.3)	0.04(.4)	0.11(.1)	0.06(.3)	0.21(.05)
He-shell burning: *LMS AGB model:*						
(ib) 'Main' s-process:	4.1	0.92	1.52	0.52	1.92	[0.19 / 0.24]
He-core burning: (iib)'Weak' s-process:	0.06	0.04	0.06	0.01	0.04	0.00
Explosive nucleosynthesis: (iii) p-process: (Type Ia, normalized to ^{92}Mo)	2.6	0.04	0.05	0.03	0.02	0.03
r-process residuals: [BSS - (ib+iib+iii)]	*(-)*	*0.28*	*0.33*	*0.14*	*0.00*	*[0.10 / 0.05]*
ANOMALY MODELLING:						
Assume N_r:	0.08	0.08	0.08	0.08	0.08	0.08
N_r/N:	0.014	0.063	0.041	-----	0.040	0.25
If η = +0.10%, (η = *r* -process excess), then:						
$\varepsilon = (\eta)(N_r/N)$:	+0.14	+0.63	+0.41	-----	+0.40	+2.5
$\varepsilon(^{i}Zr/^{94}Zr)$:	-0.26	+0.23	+0.01	-----	(Reference)	+2.1
Renormalize to N = $^{91}Zr/^{94}Zr$:						
ε_{RN}:	-0.57	N	-0.14	-----	N	+2.3

Figure 7. MODEL ANOMALY (Flat N_r = 0.08 distribution):