A NEW MEMBER OF THE "FUN" FAMILY.

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Two mineralogical unremarkable Allende inclusions, C1 and EK1-4-1, characterized by coupled mass fractionation (F) and unknown nuclear (UN) isotopic effects in many elements are the most valuable examples of heterogeneities caused by the incomplete mixing of nucleosynthetic components. A mineralogically unusual Allende inclusion HAL (for Hibonite ALlende), which consists of a hibonite core, a black rim of Al-Fe oxide, and a friable rim containing both low and high temperature minerals, has recently been discovered. Mg and Ca isotopic studies were recently published [1] which showed that HAL is a new member of the FUN family. In this paper we summarize the characteristics of HAL and compare HAL with C1 and EK1-4-1. Petrographic and trace element studies of HAL are presented elsewhere in this volume [2,3].

Hibonite is the most refractory and possibly the most primitive major element oxide. The hibonite in HAL is of particular interest because it is close to pure $CaAl_{12}O_{19}$ and is the only coarse-grained sample of this key phase. HAL hibonites have high $^{27}Al/^{24}Mg \sim 1200$ and would have shown ^{26}Mg excesses of $\sim$500‰ if its initial $(^{27}Al/^{26}Al)_o$ had been $\sim 5\times10^{-5}$, the value observed in some Allende inclusions[4,5]. Surprisingly, no ^{26}Mg excess was found and the upper limit 2‰ implies that the ^{26}Al content of HAL was at least 250 times lower than that of some other Allende inclusions consisting of lower temperature minerals. There is also no large Mg fractionation and the limit is 20‰ per amu for hibonite and 10‰ for other phases.

All phases in HAL show large but uniform Ca isotopic shifts Δ_i($\Delta_i \equiv [(Ca^i/Ca^{44})(\text{sample})/(Ca^i/Ca^{44})(\text{normal})] - 1$) which are dominated by large fractionation of 7.5‰ per amu favoring the heavy isotopes (Fig.1). Additional non-linear effects of presumably nuclear origin at the level of $\sim$2‰ is also present but there is no unique way to decompose the shifts Δ_i and extract nuclear effects δ_i. If the fractionation effect is exactly linear (L) in mass and if the nuclear effects δ_j and δ_k are known for two "basis" isotopes j and k, then the nuclear effects δ_i for all other isotopes can be obtained using

$$L\delta_i^{jk} = \Delta_i - \{(\Delta_j - \delta_j) + [(\Delta_j - \delta_j) - (\Delta_k - \delta_k)] \cdot (m_i - m_j)/(m_j - m_k)\} \qquad (1)$$

where m_i is the mass. Therefore, depending on the choice of and assumption on the basis isotopes, there are many representations for the nuclear effects. Furthermore, for highly fractionated samples like HAL, δ_i also depends on the exact form of the fractionation law. Similar expressions for other laws (e.g., Rayleigh distillation (R)) can be derived. We have chosen ^{40}Ca and ^{44}Ca as basis isotopes in [1] to minimize errors and assumed that $\delta_{40}=\delta_{44}=0$ to obtain $L\delta_i^{40\ 44}$ and $R\delta_i^{40\ 44}$ (cf. Fig.1). Nucleosynthetic models may be used to guide the choice of the basis isotopes. For example, if both ^{40}Ca and ^{42}Ca are produced in explosive O burning [16] then one may hope that using them as basis would reveal some trends (e.g., all other isotopes show excesses). However, $L\delta_i^{40\ 42}$ in Table 1 do not show any such obvious systematics. The representation in Table 1 supports the previous conclusion that the incomplete mixing of at least three Ca components is requred to explain the combined data of HAL, C1 and EK1-4-1.

In Table 2 the characteristics of HAL are summarized schematically and compared to those of C1 and EK1-4-1. Table 2 shows that (A) All FUN effects are uniform for all elements except O within each object; (B) For Mg and Ca, and possibly also Si, samples showing large F in one element always show UN in

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the same element. (C) F in Mg and Si are correlated but they do not correlate with F in Ca; the O effects also correlate with Mg and Si and can be explained by F coupled to the usual ^{16}O-normal mixing. (D) There are both excesses and deficits in UN effects on the same isotope in different samples and both sample having deficits and sample having excesses show F. (E) $^{26}Al/^{27}Al$ in two of the FUN objects are low relative to usual Allende inclusions.

As hinted by the fact (B) above, UN may be suspected to be artifacts associated with large fractionation. However, we note that the reverse of (B) is not always true, i.e., there are UN effects in some samples that do not show large F in the same element. In addition, the magnitudes of UN generally do not correlate with the extent of F contrary to what one would expect from artifacts associated with large F (e.g., Mg [10]). Furthermore, for Ba, Nd and Sm, there seems to be a systematic dependence of UN on nuclear properties such as neutron numbers, shielding from β-decay, etc. Therefore, we believe that UN is not from either mass fractionation or mass separation but represents isotopic heterogeneities due to the incomplete mixing of nucleosynthetic components.

The presence of ^{26}Al in the early solar system and the new evidence for extinct ^{107}Pd [6] suggests that certain nuclear events capable of producing both low and high Z elements occurred immediately before the solidification in the solar system. A possible source for UN is this last event. Fact (E) does not support this possibility but still allows a model in which the ^{26}Al and UN were from the same source. Let us suppose that the present normal contains some contaminants from the last event which produced UN and ^{26}Al and that fact (D) should be interpreted as that some FUN objects received more contaminants than the normal while some received less. Then, it is expected that those less contaminated ones should have less ^{26}Al than the normal and show deficits in UN relative to the normal. In this model the low ^{26}Al is due to amplified spatial heterogeneity which is also expected because UN from the last event was diluted by material from previous events while ^{26}Al would all come from the last event. Inspection of Table 2 shows that the UN in Cl can be ex-

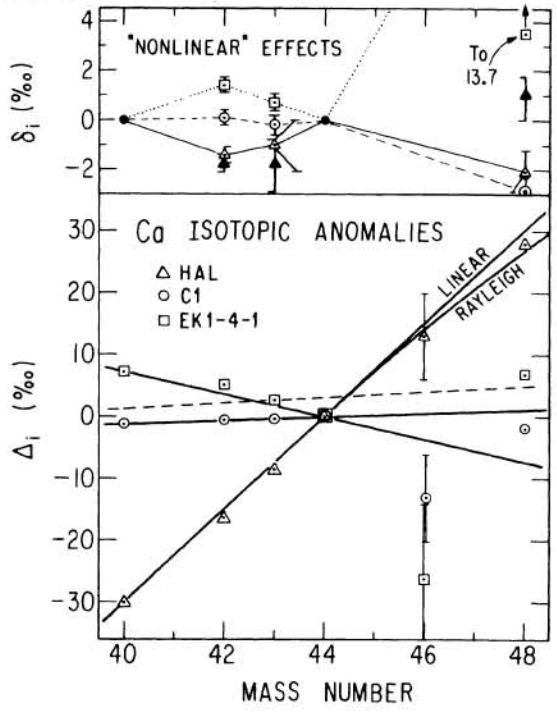

TABLE 1 Ca NUCLEAR EFFECTS[a]

Sample	$L_{\delta_{43}}$	$L_{\delta_{44}}$	$L_{\delta_{46}}$	$L_{\delta_{48}}$ [b]
HAL	1.1±0.9	2.8±0.3	2±7	3.7±1.2
C1	-1.2±0.6	0.4±0.4	-14±7	-3.7±0.9
EK1-4-1	-1.7±0.7	-3.3±0.3	-27±13	7.1±0.9

a) Permil nuclear effects $L_{\delta_i}^{40\ 42}$ calculated using eq. (1) with ^{40}Ca and ^{42}Ca as basis isotopes and $\delta_{40}=\delta_{42}=0$. b) Due to the possible deviation from the exact linear law, there may be additional large uncertainties which are not included in the error estimate.

FIGURE 1: Fractional differences of Ca isotopic ratios relative to normal (corrected for laboratory fractionation). Solid lines are fractionation curves through base isotopes ^{40}Ca and ^{44}Ca. "Linear" and "Rayleigh" refer to different fractionation laws. For EK1-4-1 and C-1 there is little difference between these two laws. Deviations from the linear curve, L_{δ_i}, due to "non-linear" effects of presumably nuclear origin are plotted in the upper panel. Solid triangles are R_{δ_i} for HAL relative to the Rayleigh curve. The broken line in the lower panel is an arbitrary but permissible choice of fractionation curve for EK1-4-1 and illustrates the major changes in the nuclear effects (non-negative δ's for all isotopes except ^{44}Ca) which can result from a different decomposition procedure.

Fig. 1 reproduced courtesy of *THE ASTROPHYSICAL JOURNAL*

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A NEW "FUN" INCLUSION

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TABLE 2 COMPOSITION OF FUN OBJECTS[a]

Sample	Mineralogical	Elemental	Isotopic (always uniform within each object)														$\left(\frac{^{26}Al}{^{27}Al}\right)_o$[c]
			O[b]		Mg		Si		Ca		Sr	Ba	Nd	Sm			
			F	UN	F	UN	F	UN	F	UN	(No large F)						
HAL	unusual	Ce low	?		0	0	?		+	x	?	?	?	?			<1/250
C1	usual	Ce low	+	x	+[d]	x	+	x	0	x	p↓[e]	r↓[f]	0	p↑			<1/10
EK-1-4-1	usual[g]	?	+	x	+	x	+	x	-[h]	x	p↓	r↑	r↑	p,r↑			?

a) compiled from [1,3,8-15], ? = no published measurement, 0 = no effect, + = heavy isotopes favored, - = light isotopes favored, p = proton rich isotopes, r = neutron rich unshielded isotopes, ↑ = abundance above normal, ↓ = abundance below normal, x = effect present; b) not uniform, usual inclusions have UN due to ^{16}O excess, FUN data can be explained by the same UN but with couple F; c) relative to the "typical" value $\sim 5 \times 10^{-5}$; d) Mg not uniform in some minor phases; e) discoverers favor other interpretation; f) except Ba^{137}; g) no detailed petrographic description; h) may be purely due to UN.

plained by deficits in r- and p-nuclides except for Sm. Fig.1 shows that UN for Ca in C1 can be explained by a deficit in ^{48}Ca. Thus the low ^{26}Al in C1 is consistent with the model. The only UN in HAL is for Ca which can be explained by a deficit in ^{42}Ca and thus may be also consistent. Therefore the low ^{26}Al in C1 and HAL does not rule out the possibility that UN was produced in the last event with ^{26}Al. The search for a positive correlation between ^{26}Al and certain UN effects is needed to test this model.

An alternative to this model is that UN was not produced with ^{26}Al but was the result of variations in the relative proportion of various nucleosynthetic components, possibly carried in pre-solar interstellar dust, whose average represents the normal. If dust was involved, fact (A) requires that no dust was preserved and hence equilibration has taken place probably during a late heating event. In this model the low ^{26}Al is due to either a coincidence in spatial heterogeneity or, more plausibly, the Mg equilibration during the heating event subsequent to the decay of ^{26}Al.

It is interesting to consider whether F can also be generated by the heating event through evaporative loss. Most F favor heavy isotopes and can be so explained if the FUN objects are evaporative residues. The possible F favoring the light isotopes in the Ca of EK1-4-1 cannot be easily explained by evaporation, especially when F in Mg, Si and O favor the opposite direction. Furthermore, the mass loss needed to explain the F is likely to be large. For example, if a Rayleigh law can be used to describe the F during evaporation then C1 must have lost 80% of the Mg. The fact that C1 has a mineralogical and chemical composition full of Mg-rich minerals (e.g., spinel) and is indistinguishable from typical Allende inclusions without Mg fractionations poses a problem for this explanation [7]. However, the mineralogy of HAL is unusual and may be consistent with that of an evaporative residue.

The link between F and UN is the most critical issue yet to be explained. Complicated chemical history as evidenced by the lack of correlation between F in Mg and F in Ca, and the Ce elemental anomalies may have added confusion to this matter.

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