RARE-EARTHS IN THE ALLENDE INCLUSION, EK 1-4-1 AND THE ORIGIN OF ALLENDE INCLUSIONS. H. Nagasawa, Gakushuin University, Mejiro, Tokyo 171, Japan, D.P. Blanchard, Johnson Space Center, NASA, Houston, TX 77058, H. Shimizu and A. Masuda, Kobe University, Kobe 657, Japan.

The Allende inclusion EK 1-4-1 has shown to have isotope anomalies of O, Mg, Ca, Sr, Ba, Nd and Sm, together with the correlated mass fractionation of Mg and O(1-6). These unique characters of the inclusion indicates that this specimen provides us numerous informations on nucleosynthetic processes and early cosmochemical processes which followed the nucleosynthetic processes.

We have analyzed rare earth elements (REE) in EK 1-4-1 and found that EK 1-4-1 have unique REE abundances and disequilibrium distribution of REE between melilite and pyroxene. Based on the available data on EK 1-4-1 and other Allende inclusions, we propose a 'partial melting' hypothesis for the origin of the heterogeneous distribution of O isotopes in the Allende coarse-grained inclusions. This hypothesis is essentially a modification of the 'partial exchange' hypothesis by Clayton and Mayeda (1), i.e. in the exchange process of O between melilite with anomalous O isotope ratio and a 'normal O' atmosphere melilite is replaced by a Ca, Al-rich melt from which melilite, anorthite, grossular etc were crystallized.

The observed REE abundance patterns in the fractions of EK 1-4-1 are shown in Fig. 1. REE patterns for bulk sample and impure fractions (Fig.1a) indicate that EK 1-4-1 has an unusual REE abundance pattern which is enriched in light REE, La to Eu, decreasing from Eu towards Lu with an Yb anomaly. This pattern is very similar to that calculated by Boynton (7) for that in a gas of the primitive solar nebula left after condensation of the most refractory REE (Fig. 2). The REE patterns in melilite and pyroxene fractions in Fig. 1b shows that REE distribution between the minerals are different from those observed for normal Allende coarse-grained inclusions, A-15 in Fig. 1b for example, which are explained by equilibrium distribution (8).

The heterogeneous distribution of O isotopes in Allende inclusions have been explained either by mixing of two components (9) or incomplete O exchange reaction between minerals with pure $^{16}O$ and a normal O atmosphere (10). Considering the mass fractionation of Mg and O in EK 1-4-1 and C-1, Clayton and Mayeda (1) showed that the postulate of existence of pure $^{16}O$ component is not essential for the origin of the O isotope anomalies. Instead, they suggested that EK 1-4-1 was formed originally with O isotopic anomalies distributed homogeneously followed by exchange of O in melilite, anorthite etc with a normal O atmosphere.

We have examined the 'partial exchange' hypothesis of Clayton and Mayeda on the basis of REE distribution and diffusion rates in the minerals. In EK 1-4-1 isotope anomalies of REE and other cation elements are distributed homogeneously within the inclusion (6), while REE show disequilibrium distribution between melilite and pyroxene. Since diffusion coefficients of cations observed in silicate minerals are usually several orders of magnitude larger than those of O (11, 12), cation distribution as well as isotope ratios must have been equilibrated if O isotopes in melilite was exchanged with those in a gas through diffusion.

Diffusion coefficient of O in melilite, which is not available in literature must be at least 280 times larger than that in pyroxene (13), in order to exchange 90 % of O in melilite with a normal O atmosphere while keeping exchange rate of O in pyroxene to be below 10 %. Diffusion coefficients of O in common rock-forming minerals, except that in forsterite, are $10^{-13}$ to $10^{-11} \text{cm}^2/\text{sec}$ at $1280^\circ\text{C}$ (14). It appears reasonable to assume that fassaite pyroxene in the Allende inclusions, which is a Ca, Al-rich clinopyroxene with
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A crystal structure similar to that of diopside have O isotope diffusion coefficient within the range of rock-forming minerals, possibly close to that in diopside \((1.8 \times 10^{-12} \text{ cm}^2/\text{sec})\). Then, O diffusion coefficient in melilite must be about \(5 \times 10^{-10}\) or larger to explain the observed O isotope heterogeneity. However, this value is unrealistic for melilite, since it is in the range of those in silicate melt (14). Thus, the partial exchange of O isotopes between crystal and gas is not likely to be the origin of the heterogeneity.

We assume a material composed of fassaite pyroxene and spinel with anomalous O isotope ratios which are distributed homogeneously within the material. This original material was partially melted by a later thermal event. The melted portion which have higher diffusion coefficient exchanged O isotopes with a normal O atmosphere, while spinel and pyroxene remained unmelted and did not exchange O isotopes. If the melting temperature was low, most of spinel and a part of fassaite remained unmelted and the melt produced have chemical composition, fassaite + spinel. Since melilite is not a stable phase at liquidus temperature, melilite crystallized together with anorthite, diopside, forsterite and possibly grossular at subsolidus temperatures (15,16) to produce type B inclusion. If the original material was heated to a high temperature (say, above 1500°C) at an initial stage of melting, most of the material except some spinel melted and most of PdO and some of SiO\(_2\) and MgO must have been lost by evaporation. Melilite crystallized from the Ca, Al-rich residual melt to form type A inclusion together with the unmelted spinel. Since diffusion coefficient of cations are several orders of magnitude larger than that of O in the same mineral, the melt and the remaining fassaite and spinel are equilibrated with respect to REE distributions. Thus, melilite crystallized from the melt, in most cases, have REE abundances which are close to those in melilite equilibrated with fassaite. However, cocrystallization with other minerals could change REE abundances in melilite significantly. Such a case is observed for EK 1-4-1.

The 'partial melting' hypothesis is consistent with the isotopic, elemental and mineralogical evidences observed for the coarse-grained Ca, Al-rich inclusions in the Allende meteorite and the diffusion coefficient data for the rock-forming minerals.

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Figure 1. Chondrite-normalized REE abundances in the bulk (a) and separated fractions (b) of EK 1-4-1. A: Bulk sample determined by neutron activation analysis (INAA), B: Melilite (d=3.01-3.17), INAA, C: Pyroxene (+ small amounts of grossular and spinel, d=3.31-3.54), INAA, D: spinel (d=3.54-3.72) purified by HF-HClO4 treatment, E: impure fraction (melilite+pyroxene+grossular), F: impure fraction (pyroxene+melilite+grossular). E and F were determined by massspectrometric isotope dilution method.

Figure 2. Relative REE abundances (La+1) in the fraction E and F compared with those calculated by Boynton (7) for the gas remaining after removal of the most refractory solid material.