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NOBLE GAS COMPOSITION IN UNIQUE METEORITE YAMATO-74063

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Abstract: Unique meteorite Yamato-74063 contains large amounts of trapped heavy noble gases whereas it is depleted in trapped He and Ne. The concentration of trapped ^{36}Ar is comparable with that of E- and C-chondrites and ureilites. Trapped ^{132}Xe is unusually abundant. Y-74063 contains a very high concentration of radiogenic ^{129}Xe. Trapped ^{20}Ne/^{36}Ar is low and similar to that of ureilites. Trapped ^{36}Ar/^{132}Xe of 32 ± 4 is lower than that of any meteorites ever reported. The trapped gases in Y-74063 are depleted in Ar relative to Xe. Planetary-type noble gases may be mixtures of an Ar-depleted component and the "sub-solar" or "Ar-rich" component isolated in E-chondrites. The cosmic-ray exposure age is 6.2 ± 0.4 Ma. Gas-retention ages are calculated to be less than 3.7 ± 0.2, and 4.8 ± 0.4 Ga from radiogenic ^{4}He and ^{40}Ar respectively. The K-Ar age older than the age of the solar system may attributed to chemical inhomogeneities resulting in an exceptionally high K concentration of the investigated sample. The gas-retention ages, the large amounts of radiogenic ^{129}Xe and the trapped noble gases indicate that the meteorite was a closed system for the noble gases since crystallization.

1. Introduction

Yamato-74063 (hereafter Y-74063) is a meteorite of 35.41 g, with achondritic texture but chondritic composition. It has been originally classified as unique chondrite by YANAI and KOJIMA (1987). According to YANAI and KOJIMA (1990), it is texturally, mineralogically, and chemically similar to Acapulco and Lodran, which lie between E- and H-chondrites on a %Fa *vs.* %Fs diagram. The meteorite consists of relatively coarse-grained olivine and pyroxene with Fa=10.9 and Fs=10.9%, respectively. It also contains minor amounts of iron-nickel, troilite and plagioclase. The Fe-Ni metal content is similar to that of L-chondrites. The Fe content in silicates and the FeS content are intermediate between ordinary chondrites and E-chondrites. Y-74063 is distinct from known chondrite classes on an oxidized Fe *vs.* metal Fe+FeS diagram (YANAI and KOJIMA, 1990). NAGAHARA *et al.* (1990) suggest that the meteorite was formed in a melt pocket in a chondritic body without significant loss of partial melt.

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2. Experiment and Results

A chip of 91.97 mg, delivered from NIPR, was used for the noble gas analysis. The sample was heated in a side-arm of a sample holder at about 100°C overnight to outgas adsorbed atmospheric noble gases. Noble gases were extracted by a single step heating at 1750°C for 25 min, and measured by mass spectrometry (TAKAOKA, 1976; TAKAOKA and NAGAO, 1978). Blanks are: ^{4}He$=1.8\times10^{-9}$, ^{20}Ne $<1\times10^{-11}$, ^{36}Ar$=7\times10^{-12}$, ^{84}Kr$=6\times10^{-13}$ and ^{132}Xe $<1\times10^{-13}$ cm^3 STP. Correction for doubly-charged ^{40}Ar and CO$_2$ is <0.1% and 4%, respectively. Noble gas data are given in Tables 1 and 2. Errors for noble gas concentrations are 10%, and errors cited for isotopic ratios are statistical ones with 95% confidence.

Table 1. Noble gases in Y-74063.

Samle	^{4}He	^{3}He/^{4}He	^{22}Ne	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{36}Ar	^{38}Ar/^{36}Ar
Y-74063	16100	5.95±0.35 $\times10^{-3}$	15.3	1.553 ±0.013	0.709 ±0.007	1560	0.190 ±0.0008

Sample	^{40}Ar/^{36}Ar	^{84}Kr	^{132}Xe
Y-74063	35.6 ±0.2	30.0	48.4

Noble gas concentrations are given in units of 10^{-9} cm^3/g.

Table 2. Kr and Xe isotopic ratios for Y-74063.

Sample	^{78}Kr/^{84}Kr	^{80}Kr/^{84}Kr	^{82}Kr/^{84}Kr	^{83}Kr/Kr^{84}	^{86}Kr/^{84}Kr
Y-74063	0.00636 ±0.00020	0.04006 ±0.00044	0.2041 ±0.0019	0.2044 ±0.0018	0.3133 ±0.0019

Sample	^{128}Xe/^{132}Xe	^{129}Xe/^{132}Xe	^{130}Xe/^{132}Xe	^{131}Xe/^{132}Xe	^{134}Xe/^{132}Xe	^{136}Xe/^{132}Xe
Y-74063	0.0833 ±0.0018	1.095 ±0.018	0.1642 ±0.0026	0.8210 ±0.0059	0.3867 ±0.0042	0.3240 ±0.0066

For decomposition of noble gas compositions, the following isotopic ratios are used: ^{3}He/^{4}He$=0.2$ for spallogenic He, ^{20}Ne/^{22}Ne$=12.52$ and ^{21}Ne/^{22}Ne$=0.0335$ for solar Ne, ^{20}Ne/^{22}Ne$=8.2$ and ^{21}Ne/^{22}Ne$=0.024$ for planetary Ne, and ^{20}Ne/^{22}Ne$=0.85$ for spallogenic Ne. For trapped and spallogenic Ar, ^{38}Ar/^{36}Ar$=0.188$ and 1.65, respectively, are used (OZIMA and PODOSEK, 1983 and references cited therein). Radiogenic ^{129}Xe is calculated by assuming trapped $(^{129}\mathrm{Xe}/^{132}\mathrm{Xe})_t=1.025$ that is the ratio for the Novo Urei ureilite (MARTI, 1967).

3. Discussion

Helium is a mixture of trapped, spallogenic and radiogenic components. Y-74063 is depleted in trapped He and Ne. Neon is a mixture of trapped Ne and spallogenic Ne because measured ^{20}Ne/^{22}Ne is higher than the spallogenic ratio. In contrast, Ar is dominated by the trapped component and the radiogenic component

(^{40}Ar). The ^{36}Ar concentration is extremely high compared to ordinary chondrites (SCHULTZ and KRUSE, 1989) except solar-gas-rich meteorites (WASSON, 1974), and is in the ranges for E-chondrites, C-chondrites and ureilites. Enrichment of trapped ^{132}Xe overwhelms E- and C-chondrites (CRABB and ANDERS, 1981; MAZOR *et al.*, 1970) and even ureilites (GÖBEL *et al.*, 1978) except Dyalpur (MAZOR *et al.*, 1970) and ALH-77257 (TAKAOKA, 1983).

3.1. *Spallogenic gases and cosmic-ray exposure ages*

We assume all ^{3}He to be spallogenic. With spallogenic ^{3}He/^{4}He of 0.2, 3% of measured ^{4}He, or 4.8×10^{-7} cm^3 ^{4}He/g, is spallogenic and the remaining fraction is radiogenic and trapped. ^{21}Ne is mostly spallogenic. Since the isotopic ratio of trapped Ne is unknown, the exact spallogenic $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{\mathrm{sp}}$ ratio cannot be calculated. However, with the assumption of two-component mixing between spallogenic and trapped Ne that is solar or planetary, $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{\mathrm{sp}}$ is estimated to be between 1.28 and 1.33, appreciably higher than the average chondritic value of 1.11. The high $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{\mathrm{sp}}$ is compatible with high $(^{3}\mathrm{He}/^{21}\mathrm{Ne})_{\mathrm{sp}}$ of 8.9 (Table 3). These ratios fall on the ^{3}He/^{21}Ne *vs.* ^{22}Ne/^{21}Ne correlation line given by EBERHARDT *et al.* (1966), indicating no loss of spallogenic ^{3}He and ^{21}Ne. This result on spallogenic He and Ne indicates cosmic-ray exposure at shallow shielding or in a small meteoroid. A small meteoroid is compatible with the small recovered mass of 35.41 g.

Table 3 gives the spallogenic He and Ne. Cosmic-ray exposure ages can be calculated from both $^3\mathrm{He}_{\mathrm{sp}}$ and $^{21}\mathrm{Ne}_{\mathrm{sp}}$. Since Y-74063 is similar to LL-chondrites in Mg and Si contents (YANAI and KOJIMA, 1990) that give high ^{21}Ne yields, the production rates given by EUGSTER (1988) for LL-chondrites are used. The ^{21}Ne production rate given by NISHIIZUMI *et al.* (1980) and the production rates by CRESSY and BOGARD (1976) are also used for comparison. The result on the exposure ages is given in Table 3. The exposure ages from $^3\mathrm{He}_{\mathrm{sp}}$ and $^{21}\mathrm{Ne}_{\mathrm{sp}}$ are 6.3 ±0.7 and 6.2 ±0.6 Ma, respectively. The shielding correction was calculated on average $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{\mathrm{sp}}$ of 1.31± 0.2. The ^{21}Ne age by NISHIIZUMI *et al.* and the ^{3}He age by CRESSY and BOGARD

Table 3. Cosmic-ray exposure ages and gas-retention ages.

Sample	$^3\mathrm{He}_{\mathrm{sp}}$	$^{21}\mathrm{Ne}_{\mathrm{sp}}$	$(^{3}\mathrm{He}/^{21}\mathrm{Ne})_{\mathrm{sp}}$	$(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{\mathrm{sp}}$	P_3	P_{21}
	($\times10^{-9}$cm^3/g)				($\times10^{-9}$cm^3/gMa)	
Y-74063	96.1	10.8	8.9	1.28±0.02[1)]	15.3±0.5[3)]	1.75±0.19[3)]
	±9.6	±1.1	±1.2	1.33±0.01[2)]	—	1.63±0.05[4)]
					16.0±1.6[5)]	2.69±0.27[5)]

Sample	T_3	T_{21}	$^4\mathrm{He}_{\mathrm{r}}$	$^{40}\mathrm{Ar}_{\mathrm{r}}$	U (U/Th) (ppb)	K (wt%)	T_4	T_{40}
	(Ma)		($\times10^{-9}$cm^3/g)				(Ga)	
Y-74063	6.3±0.7	6.2±0.9	<15600	55500	=13 (=3.6)	=0.06	<3.7	4.8[6)]
	—	6.6±0.7	±1600	±5600			±0.2	±0.4
	6.0±0.8	4.0±0.6						

[1)] Trapped Ne: planetary, [2)] Trapped Ne: solar, [3)] EUGSTER (1988), [4)] NISHIIZUMI *et al.* (1980), [5)] CRESSY and BOGARD (1976), [6)] Including 20% error for K content.

agree well with the result given by EUGSTER, but the ^{21}Ne production rate by CRESSY and BOGARD gives a significantly younger age of 4 Ma. From the above result except the ^{21}Ne age by CRESSY and BOGARD the cosmic-ray exposure age for Y-74063 is 6.3± 0.4 Ma.

3.2. Radiogenic gases and gas-retention ages

An upper limit of radiogenic ^{4}He in Y-74063 is 1.56×10^{-5} cm^3/g. No data on the U and Th contents are available. With an assumption of U=13 ppb and Th/U= 3.6, which are the average values for ordinary chondrites (MORGAN, 1971), an upper limit of the ^{4}He age is 3.7±0.2 Ga. The concentration of ^{40}Ar is 5.55×10^{-5} cm^3/g. With the assumption that all ^{40}Ar is radiogenic and the K content for our sample is the same as that (0.06 wt%) given by YANAI and KOJIMA (1990), the gas-retention age from ^{40}Ar is 4.8 Ga. This nominal age exceeds the age of the solar system. Considering uncertainties from noble gas analysis (±10%) and from inhomogeneity of chemical composition (say, ±20%), the uncertainty attached to the K-Ar age is ±0.4 Ga. Hence, the above K-Ar age is compatible with the age of the solar system within experimental uncertainty. Radiogenic ^{129}Xe amounts to 3.44×10^{-9} cm^3/g, which is more abundant than that for ureilites, C-chondrites and most of E-chondrites. The enrichment of ^{129}Xe$_r$ and the old gas-retention ages indicate that the meteorite kept a closed system against noble gas loss since crystallization.

3.3. Trapped gases

Trapped ^{20}Ne is calculated to be 1.15×10^{-8} or 1.20×10^{-8} cm^3/g, depending on the solar or planetary value for $(^{20}\mathrm{Ne}/^{22}\mathrm{Ne})_t$, respectively. Trapped ^{4}He is less than 6×10^{-6} cm^3/g that is an upper limit calculated from trapped ^{20}Ne of 1.2×10^{-8} cm^3/g, assuming solar ^{4}He/^{20}Ne of 500 (GEISS *et al.*, 1972). The trapped component is predominant in Ar, Kr and Xe. The ^{36}Ar concentration is higher than that for any unequilibrated ordinary chondrites and comparable with that for E- and C-chondrites, and ureilites (SCHULTZ and KRUSE, 1989). Enrichment of trapped gas is particularly large for Xe. The ^{132}Xe concentration for Y-74063 is higher than for E- (CRABB and ANDERS, 1981) and C- (MAZOR *et al.*, 1970) chondrites and even for ureilites (GÖBEL *et al.*, 1978) except Dyalpur (MAZOR *et al.*, 1970) and ALH-77257 (TAKAOKA, 1983).

In Fig. 1, the various noble gas components in Y-74063, and other meteorites and meteorite classes are compared. In spite of similarity to Acapulco and Lodran in mineral chemistry (YANAI and KOJIMA, 1990), Y-74063 is different from them in the abundant trapped noble gases. In addition, $(^{20}\mathrm{Ne}/^{36}\mathrm{Ar})_t$ is considerably below the range for C-chondrites, Acapulco (PALME *et al.*, 1981) and Lodran (ZÄHRINGER, 1968) and in the ranges for E-chondrites and ureilites, while $(^{36}\mathrm{Ar}/^{132}\mathrm{Xe})_t$ is lower than for any meteorites and meteorite classes.

The high ^{132}Xe content with low $(^{36}\mathrm{Ar}/^{132}\mathrm{Xe})_t$ found in Y-74063 is difficult to be created from noble gases of solar elemental composition (*e.g.*, OZIMA and PODOSEK, 1983). If noble gases implanted, for instance, in 12001 bulk (EBERHARDT *et al.*, 1972) are the starting material, then ^{36}Ar should be decreased by a factor of 300, to give the low $(^{36}\mathrm{Ar}/^{132}\mathrm{Xe})_t$. Such large Ar-loss should cause large isotopic fractionation.

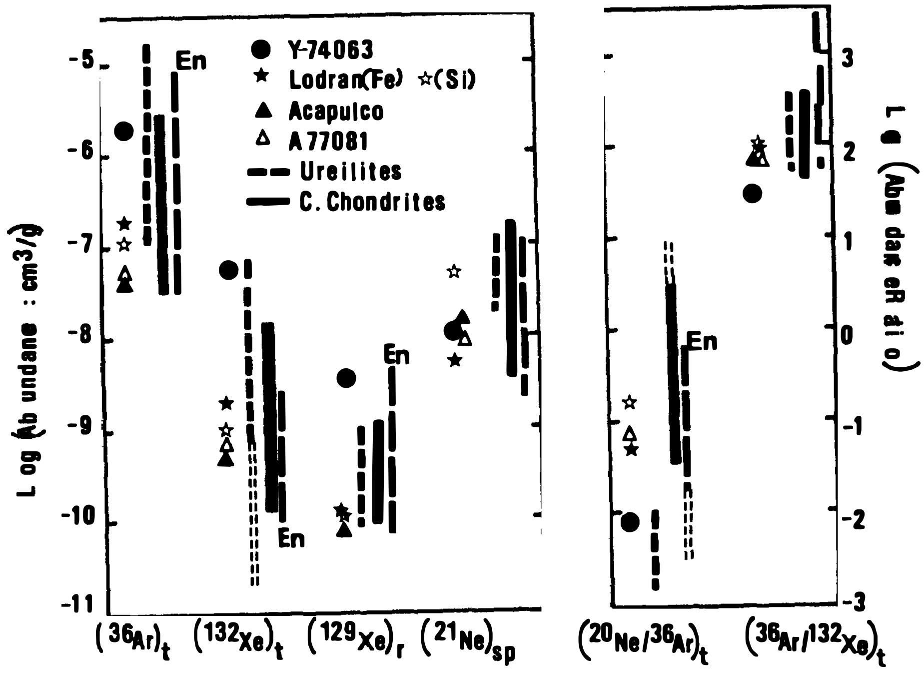

Fig. 1. Comparison of noble gas abundances and abundance ratios between Y-74063 and other meteorites and meteorite classes.

If Ar was lost through a mass-dependent process, a simple calculation on the Rayleigh process gives that residual Ar should be enriched in ^{38}Ar by 15% relative to ^{36}Ar. But no evidence for such a large isotopic fractionation is found because $(^{38}\text{Ar}/^{36}\text{Ar})_t$ corrected for spallogenic Ar is 0.190. If the trapped gases in Y-74063 originated from noble gases of planetary elemental composition, a question to be answered is what minerals would trap so large amounts of gases. Trapped gases in C-chondrites and ureilites reside in carbonaceous materials (OTT *et al.*, 1981; GÖBEL *et al.*, 1978). However, carbonaceous matter has not been reported for Y-74063. $(^{36}\text{Ar}/^{132}\text{Xe})_t$ of 32 is the lowest so far reported for meteorites. Some elemental fractionation resulting from trapping characteristics of carrier phases should work to lower ^{36}Ar/^{132}Xe from planetary ratio of 90 (MAZOR *et al.*, 1970) to 32.

An alternative explanation is that the trapped gases in Y-74063 may be enriched in an "Ar-poor" component that gives noble gases found in E- and C-chondrites and ureilites by mixing with a complementary component of high ^{36}Ar/^{132}Xe. Figure 2 is a plot of ^{36}Ar/^{132}Xe *vs.* 1/^{132}Xe. C-chondrites except CO3 give a correlation line (I) of a nearly zero slope. Such a correlation line can be produced by acquiring varied amounts of Xe with constant ^{36}Ar/^{132}Xe. CO3-chondrites and C1-chondrite Ivuna (MAZOR *et al.*, 1970), unique chondrites Sharp (H3) (ZADNIK, 1985) and ALH-77015 (L3) and its family (TAKAOKA *et al.*, 1981) and unique meteorite Kakangari (SRINIVASAN and ANDERS, 1977) define a steep correlation line (II). Ureilites seem to define a different line (III). These meteorites have appreciably high ^{36}Ar/^{132}Xe compared to meteorites correlated on the line (I). Unique meteorites Acapulco and ALH-77081 (SCHULTZ *et al.*, 1982), and Lodran are correlated on the line (I). Y-74063 is plotted distinctively below the correlation line (I), suggesting that the

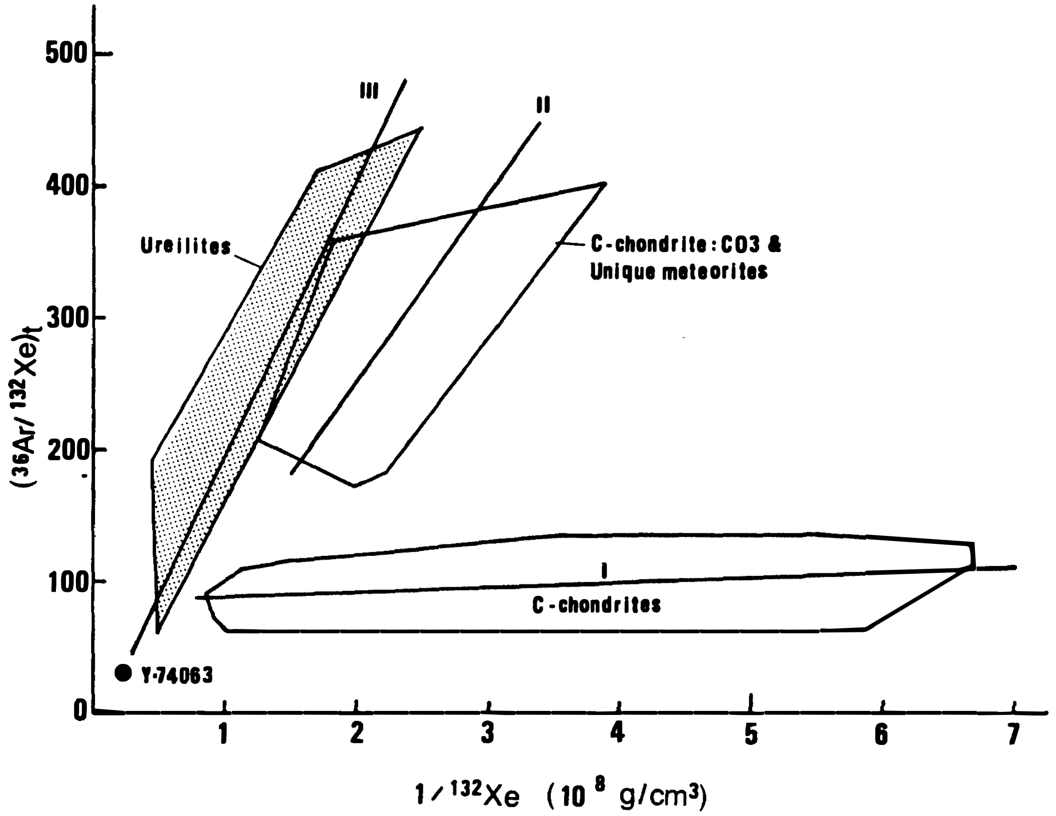

Fig. 2. A ^{36}Ar/^{132}Xe vs. 1/^{132}Xe plot. Y-74063 is plotted off data fields which give correlation lines (I), (II) and (III). It does not fit correlation line (I), which is given by C-chondrites except CO3. It rather fits correlation line (III), which is given by ureilites (bulk).

trapped noble gas in Y-74063 has a different origin from the planetary gas found in C-chondrites. It likely fits rather a lower end of extended correlation lines (II) and (III). This suggests that the trapped gas in Y-74063 is enriched in an Ar-depleted component defining the correlation lines (II) and (III). On the other hand, Novo Urei (Ur) contains noble gases of ^{36}Ar/^{132}Xe as low as 60 (Mazor *et al.*, 1970), while ^{36}Ar/^{132}Xe in carbon residues of Novo Urei is higher than 120 (Göbel *et al.*, 1978). Another noble gas carrier in Novo Urei should retain gases of low ^{36}Ar/^{132}Xe. Although the gases with ^{36}Ar/^{132}Xe lower than 60 have not been separated from Novo Urei and other ureilites, the noble gas found in Novo Urei also suggests the existence of the Ar-depleted component.

This view is supported by the correlation on a ^{36}Ar/^{132}Xe *vs.* ^{84}Kr/^{132}Xe diagram, as shown in Fig. 3. Y-74063 is plotted below the lower end of data field including E-chondrites, C-chondrites, ureilites and some ordinary chondrites. The upper end of the data field is South Oman (E4–5; Crabb and Anders, 1981), which is enriched in sub-solar (Crabb and Anders, 1981) or Ar-rich (Wacker and Marti, 1983) component. By mixing the two end-members of the "Ar-poor" and "Ar-rich" components, the planetary noble gases found in E- and C-chondrites, ureilites and other classes of meteorites would be reproducible. Both solar-type and atmospheric gases are off this correlation (Fig. 3).

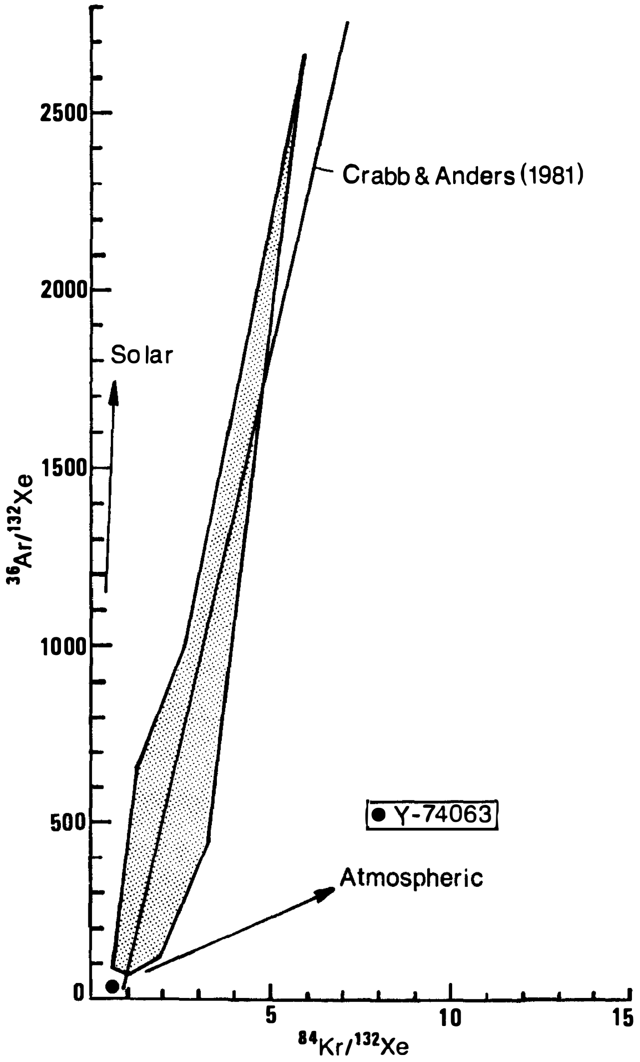

Fig. 3. *A $^{36}Ar/^{132}Xe$ vs. $^{84}Kr/^{132}Xe$ plot. Data for most of E- and C-chondrites, and ureilites fall in the shadow area. A correlation line given by* CRABB *and* ANDERS *(1981) for E-chondrites is also shown. Abundance ratios in the shadow area are reproducible by mixing an "Ar-poor" component represented by trapped gases in Y-74063 with an "Ar-rich" component represented by those in South Oman (E4–5; located at the top of shadow area). Data shifting to right-hand side may be due to atmospheric contamination.*

The isotopic ratios of Kr and Xe are given in Table 2. The isotopic ratios of Xe are indistinguishable from those of AVCC-Xe (EUGSTER *et al.*, 1967). The Kr isotopic composition, compared with that for AVCC-Kr (EUGSTER *et al.*, 1967), reveals slight excesses at both light and heavy isotopes. This excess pattern is enhanced, when compared with solar Kr. It is essentially the same excess pattern as found in comparison between AVCC and solar Kr (EBERHARDT *et al.*, 1972), but enlarged three times. Hence, compared to AVCC-Kr, the Y-74063 Kr is enriched in a component characterizing AVCC-Kr from solar Kr.

4. Conclusion

1) Helium is a mixture of spallogenic, trapped and radiogenic gases and Ne a mixture of spallogenic and trapped gases. The meteorite is unusually abundant in trapped Ar, Kr and Xe. It also contains the very high concentration of radiogenic ^{129}Xe. The ^{132}Xe concentration exceeds even that of ureilites with a few exceptions, and $(^{36}Ar/^{132}Xe)_t$ of 32 ± 4 is the lowest of any meteorites ever reported. Trapped noble gases in Y-74063 are enriched in the Ar-depleted component. The planetary-type gases found in E-chondrites, C-chondrites, ordinary chondrites and ureilites may be mixtures between this "Ar-poor" component and the "Ar-rich" component which has been indentified in E-chondrites.

2) From radiogenic ^{4}He and ^{40}Ar, gas-retention ages of $<3.7\pm0.2$ and 4.8 ± 0.4 Ga, respectively, are calculated. The cosmic-ray exposure age is calculated to be 6.3 ± 0.4 Ma. High ratios $(^{22}Ne/^{21}Ne)_{sp}=1.31\pm0.2$ and $(^3He/^{21}Ne)_{sp}=8.9\pm1.2$ indicate cosmic-ray exposure in a small meteoroid or at a shallow shielding depth. A small meteoroid is consistent with the small recovered mass.

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