

A preliminary report on noble gases in the Kobe (CK) meteorite: A carbonaceous chondrite fall in Kobe City, Japan

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Abstract: We have investigated elemental and isotopic compositions of noble gases in the newly-fallen CK chondrite, Kobe. The relatively low concentrations of primordial heavy noble gases (Kr and Xe) and the relatively high $^{129}\text{Xe}/^{132}\text{Xe}$ ratio (6.51 ± 0.02) are similar to those found in previous studies of CK chondrites. The calculated cosmic-ray exposure age based on cosmogenic ^{21}Ne is 41 Ma, and the K-Ar age is 2.1 Ga. Based on calculated exposure ages and gas retention ages of Kobe and some other CK chondrites, it is likely that they have partially lost both radiogenic and cosmogenic He by solar heating during the time of exposure. Based on the ^{40}Ar retention age, we interpret that Kobe may also have experienced thermal events, possibly related to impacts about 2 billion years ago.

1. Introduction

The Kobe meteorite fell on September 26, 1999 in the northern part of Kobe City, Japan. Because the event occurred in the evening, many observations of the fireball were reported. The meteorite penetrated a roof of the house of Mr. Hirata and was fragmented into about 20 pieces. A total mass of 136 g was recovered. Some pieces were used for preliminary petrological and mineralogical investigations, which revealed that the meteorite is the first 'fall' of a carbonaceous chondrite in Japan, and that it has a close affinity to the Karoonda (CK) group (Nakamura *et al.*, 2000a, b; Tomeoka *et al.*, 2000).

The CK group was originally defined by Kallemeyn *et al.* (1991), based on petrology, mineralogy, major and minor elemental compositions and oxygen isotopic compositions. In terms of noble gases, Scherer and Schultz (2000) examined the elemental and isotopic compositions of eighteen CK chondrites, and showed that the CK group is characterized by having relatively low abundances of primordial heavy noble gases and high $^{129}\text{Xe}/^{132}\text{Xe}$ ratios compared with other carbonaceous groups. At present, about twenty CK chondrites have been investigated, but their origin, evolution and relationship with other groups of chondrites are not well understood.

In order to shed light on the still ambiguous history and nature of CK chondrites, the Kobe Meteorite Consortium was organized by sixteen leading laboratories in Japan and the U.S.A. Investigations were begun on two large fragments of Kobe (Kobe C

and E), which are on loan from Mr. Hirata (Nakamura *et al.*, 2000a, b). As members of the consortium, we measured the noble gas elemental and isotopic compositions of this new meteorite. In this paper, we report preliminary results of noble gas analyses on Kobe, and discuss the possible processes recorded in Kobe by estimating the cosmic-ray exposure and gas retention ages.

2. Experimental procedure

In this study, we used a chemically untreated chip of Kobe C-3-1 (27.79 mg). The sample was wrapped in Al-foil and loaded into a glass sample holder. After being baked under vacuum at about 120°C for a total of 29 hrs, the sample was dropped into a Mo-crucible and subsequently heated by a resistively-heated double vacuum Ta-furnace. The gas was extracted at 1600°C for 20 min and purified to remove active species using two Ti-Zr getters, which were heated at about 700°C for 15 min, and then cooled down for 10 min. After the purification, Ne, Ar, Kr, and Xe were adsorbed onto a cryogenic trap cooled at 18 K for 20 min. Helium remained in the gas line was introduced to a VG5400 mass spectrometer for isotopic analysis with an on-line charcoal trap held at 77 K to reduce contributions of Ar and CO₂ that build up in the lines. Following helium analysis, Ne was released from the cryogenic trap by heating it to 35 K for 15 min and was then analyzed. After the Ne measurements, Ar, Kr, and Xe (whose release temperatures were 75 K, 110 K, and 183 K, respectively) were analyzed sequentially without being exposed to the on-line charcoal trap.

The sensitivity and mass discrimination corrections for the noble gases were calibrated by analyses of aliquots of atmospheric gas of known volume and isotopic compositions and an artificial He gas mixture ($^3\text{He}/^4\text{He} = (2.862 \pm 0.049) \times 10^{-5}$).

The hot (1600°C) blank levels were 1.1×10^{-9} , 1.3×10^{-12} , 7.0×10^{-12} , 2.0×10^{-12} , and 7.5×10^{-14} cm³STP for ⁴He, ²²Ne, ³⁶Ar, ⁸⁴Kr, and ¹³²Xe, respectively. An interference on ²²Ne⁺ from CO₂⁺⁺ was corrected, but it was less than 1% for the sample. In the case of ⁴⁰Ar⁺⁺ interference, our mass spectrometer can partially resolve the ⁴⁰Ar⁺⁺ peak from the ²⁰Ne⁺ peak, therefore we directly measured ²⁰Ne⁺ peak.

3. Results

Results of our noble gas analyses on the Kobe meteorite are shown in Tables 1 to 3. The cosmogenic components, such as ³He, ²¹Ne, and ³⁸Ar, and radiogenic ⁴He and ⁴⁰Ar, appear to dominate the lighter noble gas signatures of Kobe, as was also observed previously in other CK chondrites (*e.g.* Scherer and Schultz, 2000). On the other hand, there is no obvious contribution from cosmogenic or radiogenic secondary components in the observed ⁸⁴Kr and ¹³²Xe concentrations. Thus, their concentrations are regarded as primordial.

Figure 1 plots the concentrations of primordial ⁸⁴Kr vs. ¹³²Xe observed in several carbonaceous and ordinary chondrites, and shows a clear positive correlation over three orders of magnitude variation in gas concentrations. It has been suggested that primordial Kr and Xe concentrations in carbonaceous and ordinary chondrites decrease as their petrologic type increases (Marti, 1967; Mazor *et al.*, 1970; Heymann, 1971;

Table 1. Helium, Ne and Ar in the Kobe meteorite.

[⁴ He]*	³ He/ ⁴ He	[²² Ne]*	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	[³⁶ Ar]*	³⁸ Ar/ ³⁶ Ar	⁴⁰ Ar/ ³⁶ Ar
462	0.0415 ±0.0017	15.94	0.8380 ±0.0040	0.921 ±0.013	1.24	0.841 ±0.013	364 ±22

*Gas concentrations are given in 10⁸ cm³STP/g. The errors in gas concentrations are less than 10% and include all errors in volumes of the lines, standard air etc.

Table 2. Krypton in the Kobe meteorite.

[⁸⁴ Kr]*	⁷⁸ Kr	⁸⁰ Kr	⁸² Kr	⁸³ Kr	⁸⁶ Kr
	84Kr=1				
95	0.0108 ±0.0025	0.084 ±0.035	0.247 ±0.030	0.246 ±0.032	0.298 ±0.021

*Gas concentration is given in 10¹² cm³STP/g. The error in the gas concentration is 77% owing to a large blank correction.

Table 3. Xenon in the Kobe meteorite.

[¹³² Xe]*	¹²⁴ Xe	¹²⁶ Xe	¹²⁸ Xe	¹²⁹ Xe	¹³⁰ Xe	¹³¹ Xe	¹³⁴ Xe	¹³⁶ Xe
	132Xe=1							
96.5	0.0108 ±0.0011	0.0108 ±0.0012	0.0992 ±0.0048	6.505 ±0.022	0.1617 ±0.0055	0.858 ±0.013	0.419 ±0.013	0.377 ±0.014

*Gas concentration is given in 10¹² cm³STP/g. The error in the gas concentration is less than 10% and includes all errors in volumes of the lines, standard air etc.

Kaneoka, 1989; Schultz *et al.*, 1990; Scherer and Schultz, 2000). As shown in Fig. 1, Kobe has relatively low Kr and Xe concentrations compared with those of other carbonaceous chondrites, and plots within the range defined by previously reported values for CK chondrites. The petrologic type of Kobe inferred from the gas concentrations is intermediate between CK4 and CK5, which is compatible with the classification of CK4 by Nakamura *et al.* (2000a, b) and Tomeoka *et al.* (2000). An additional support for Kobe's affinity to the CK group can be found in its Xe isotopic composition. As shown in Fig. 2, CO and CV chondrites have consistently low ¹²⁹Xe/¹³²Xe ratios (<2), whereas almost all CK chondrites have higher ratios exceeding 2. Kobe has a remarkably high ¹²⁹Xe/¹³²Xe ratio of 6.51±0.02, which is the highest value reported so far for the CK chondrites. We regard this and the relatively low concentrations of primordial Kr and Xe as strong evidence supporting our conclusion that Kobe is indeed a member of the CK group.

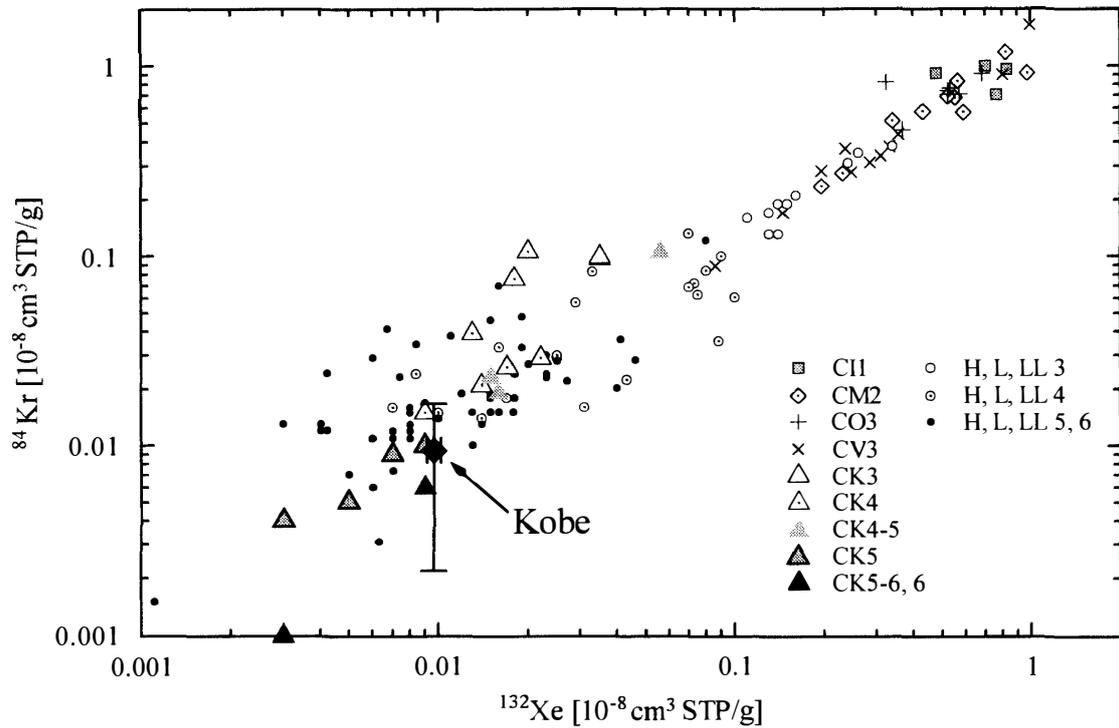


Fig. 1. A diagram of primordial ^{84}Kr and ^{132}Xe concentrations of carbonaceous and ordinary chondrites (we regard measured ^{84}Kr and ^{132}Xe concentrations as those of primordial gases). There is a good correlation between primordial Kr and Xe concentrations, which decrease with increasing petrologic type. The gas concentrations from Kobe plot in the range of concentrations typical of CK4 and CK5 chondrites. References: Kobe—this study; carbonaceous chondrites—Mazor et al. (1970), Scherer and Schultz (2000); ordinary chondrites—Zähringer (1962, 1968), Heymann and Mazor (1968).

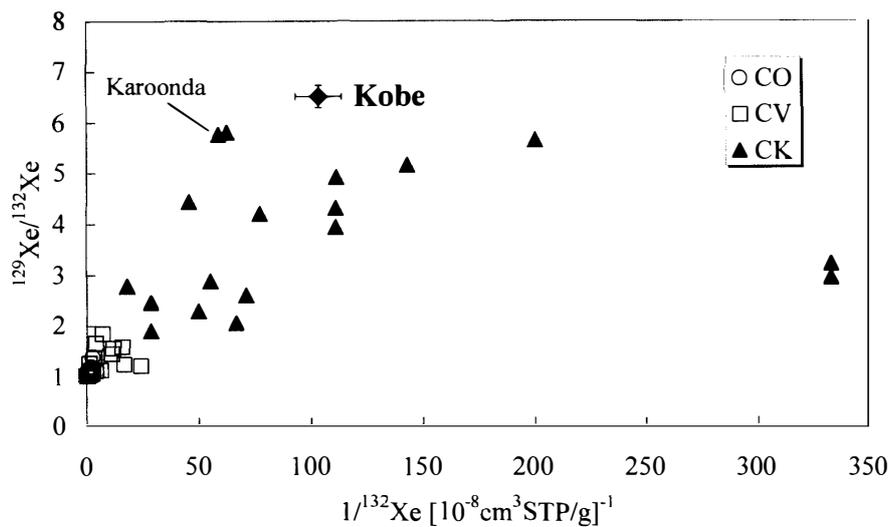


Fig. 2. A $^{129}\text{Xe}/^{132}\text{Xe}$ vs. $1/^{132}\text{Xe}$ plot. CK chondrites have low ^{132}Xe concentrations and pronounced excesses of ^{129}Xe compared with CO and CV chondrites. Kobe has the highest $^{129}\text{Xe}/^{132}\text{Xe}$ ratio in this diagram. The data of this diagram, aside from the data for Kobe, are derived from Scherer and Schultz (2000).

Other isotopic ratios, such as $^{136}\text{Xe}/^{132}\text{Xe}$, also show anomalies, but we cannot discuss them in detail from only a single step measurement. We will discuss them further from the results of stepwise heating measurements (Matsumoto *et al.*, in preparation).

4. Discussion

As we noted above, the analytical results of heavier noble gases in Kobe are quite consistent with those previously reported for other CK chondrites. We will now attempt to better elucidate the possible history of Kobe, and CK chondrites in general, by estimating exposure ages and gas retention ages from the *in situ* components observed in the lighter noble gas isotopes.

4.1. Age calculations

We calculated cosmic-ray exposure ages (T_3 , T_{21} , and T_{38}) derived from cosmogenic ^3He , ^{21}Ne , and ^{38}Ar , respectively, and U,Th- ^4He and ^{40}K - ^{40}Ar gas retention ages (T_4 and T_{40}) using the assumptions shown in the following expressions (subscripts: m = measured, p = primordial, c = cosmogenic, r = radiogenic):

$$\begin{aligned} [^3\text{He}]_c &= [^3\text{He}]_m, [^4\text{He}]_r = [^4\text{He}]_m - 5 \times [^3\text{He}]_c, \\ [^{21}\text{Ne}]_c &= [^{21}\text{Ne}]_m, (^{22}\text{Ne}/^{21}\text{Ne})_c = (^{22}\text{Ne}/^{21}\text{Ne})_m, \\ [^{38}\text{Ar}]_c &= (^{38}\text{Ar}/^{36}\text{Ar})_c \times \frac{(^{38}\text{Ar}/^{36}\text{Ar})_m - (^{38}\text{Ar}/^{36}\text{Ar})_p}{(^{38}\text{Ar}/^{36}\text{Ar})_c - (^{38}\text{Ar}/^{36}\text{Ar})_p} \times [^{36}\text{Ar}]_m, \\ (^{38}\text{Ar}/^{36}\text{Ar})_p &= 0.188, (^{38}\text{Ar}/^{36}\text{Ar})_c = 1.5, \\ [^{40}\text{Ar}]_r &= [^{40}\text{Ar}]_m. \end{aligned}$$

The production rates were evaluated using the formulae derived from Eugster (1988) with chemical correction factors ($F_3=0.99$, $F_{21}=0.97$, $F_{38}=1.02$) calculated from the mean chemical composition of CK chondrites (Lodders and Fegley, 1998).

For calculations of gas retention ages, we used decay constants (in units of $10^{-10}/\text{yr}$), $\lambda(^{238}\text{U})$, $\lambda(^{235}\text{U})$, $\lambda(^{232}\text{Th})$, $\lambda(^{40}\text{K}_\beta)$, and $\lambda(^{40}\text{K}_e)$ of 1.55125, 9.8485, 0.49475, 4.962, and 0.581, respectively (Steiger and Jäger, 1977), and isotopic abundances for elements, $^{238}\text{U}/\text{U}$, $^{235}\text{U}/\text{U}$, $^{40}\text{K}/\text{K}$ of 99.2745%, 0.7200%, and 0.01167%, respectively (Anders and Grevesse, 1989). The concentrations of U, Th, and K were assumed to be 15 ppb, 58 ppb, and 290 ppm, respectively, which are the mean values of CK chondrites (Lodders and Fegley, 1998).

4.2. Cosmic-ray exposure and gas retention ages of Kobe and other CK chondrites

The calculated ages of Kobe are listed in Table 4. If all cosmogenic ^3He , ^{21}Ne , and ^{38}Ar produced over time had been accumulated and preserved in the samples, the calculated ages from each of the three isotopes would be expected to be the same. However, there are differences in the ages determined from different isotopes in Kobe. The T_3 age is the youngest (12 ± 2 Ma), followed by T_{38} (19 ± 3 Ma) and T_{21} (41 ± 6 Ma). The T_{21} age is the least likely to be influenced by mild thermal events because host minerals of cosmogenic ^{21}Ne , such as olivine and pyroxene, are more retentive against a diffusive loss of Ne than Ca-bearing feldspars are against diffusive loss of ^{38}Ar

Table 4. Cosmic-ray exposure and gas retention ages of Kobe meteorite.

Cosmic-ray exposure ages [†] [Ma]			Gas retention ages [‡] [Ga]	
T ₃	T ₂₁	T ₃₈	T ₄	T ₄₀
12	41	19	1.0	2.1
±2	±6	±3	±0.1	±0.2

[†] The errors of exposure ages were calculated based on 10% errors in noble gas concentrations and production rates.

[‡] The errors of gas retention ages were based on 10% errors in noble gas concentrations and chemical compositions.

(Loeken *et al.*, 1992). The T₂₁ age of Kobe is in the range reported previously for CK chondrites (2–50 Ma; Scherer and Schultz, 2000).

In comparison, the observed shorter T₃ ages can be explained by preferential He loss owing to solar heating in meteoroids with small perihelion distances (Anders, 1964; Hintenberger *et al.*, 1966; Wänke, 1966; and many other researchers). Possible preferential loss of He over Ne can be recognized by using a (³He/²¹Ne)_c vs. (²²Ne/²¹Ne)_c diagram (so-called Bern Plot, Fig. 3; Eberhardt *et al.*, 1966). The solid line is a best fit for ordinary chondrite data (Nishiizumi *et al.*, 1980). The apparent correlation between (³He/²¹Ne)_c and (²²Ne/²¹Ne)_c has been interpreted to reflect shielding from cosmic-ray exposure where greater degrees of shielding would shift the data to a lower (²²Ne/²¹Ne)_c value along the line. The Kobe meteorite plots considerably below the correlation line, indicating significant preferential loss of He over Ne. Similar He loss is also observed in other meteorites, such as ALH 82135, Sleeper Camp 006, EET 87507, and EET 90026.

If ³He loss was caused by solar heating, it is expected that ⁴He would also have been lost from the meteorite to a similar extent. This is clearly supported by Eugster's diagram in which the T₃/T₂₁ and T₄/T₄₀ ratios are shown (Fig. 4; Eugster *et al.*, 1993, 1998; Scherer *et al.*, 1998). The ratios that plot along the dashed line with a slope of one show coupled loss of ³He_c and ⁴He_c from the meteorites. All the meteorites with a low (³He/²¹Ne)_c signature, including Kobe, plot along this line, suggesting the He loss may have been caused by solar heating during the time of exposure to cosmic-rays.

The calculated T₃₈ age is also shorter than the T₂₁ age in Kobe. Previous studies of ordinary chondrites showed that disagreement between T₂₁ and T₃₈ exposure ages could be eliminated by decreasing the estimated production rate of ³⁸Ar by about 10–15% (Graf and Marti, 1989, 1995; Schultz *et al.*, 1991; Eugster *et al.*, 1993; Alexeev, 1998; Scherer *et al.*, 1998). However, we did not find systematic differences between T₂₁ and T₃₈ in the majority of the CK chondrites. Thus, the apparent disagreement in exposure ages requires a different explanation. One possible explanation is preferential Ar loss. In this respect, it should be noted that the radiogenic ⁴⁰Ar might have also been lost to some extent, as the T₄₀ age derived from radiogenic ⁴⁰Ar of Kobe (2.1 Ga) is shorter than those of most carbonaceous chondrites (4.5 Ga). Although it was reported that Ar loss caused by terrestrial weathering could shorten T₃₈ and T₄₀ (Gibson

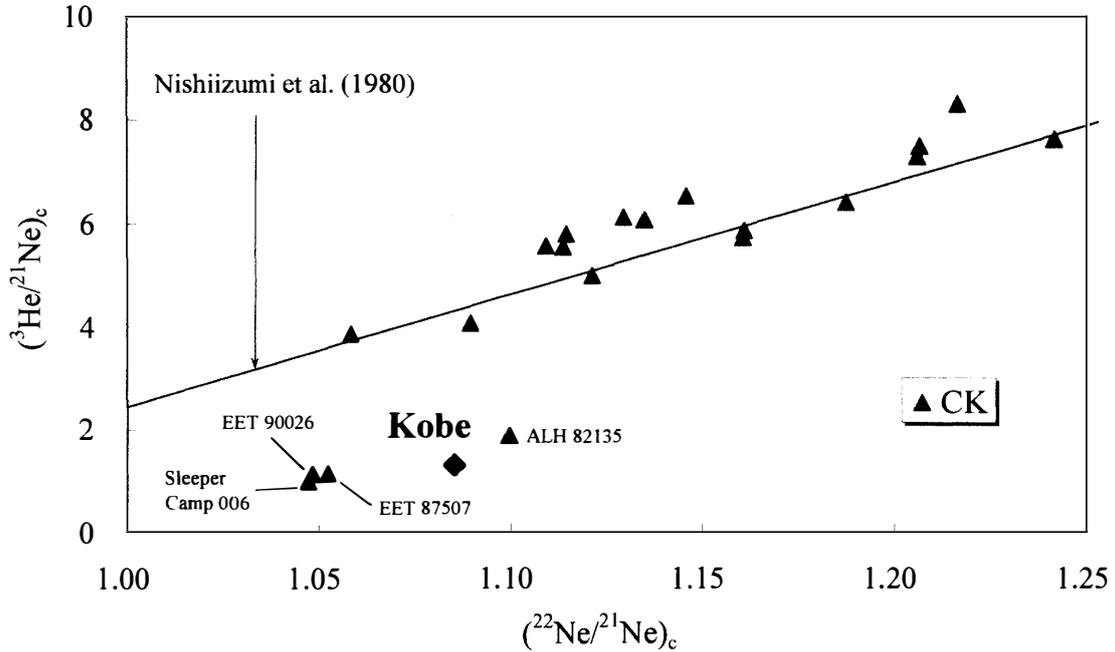
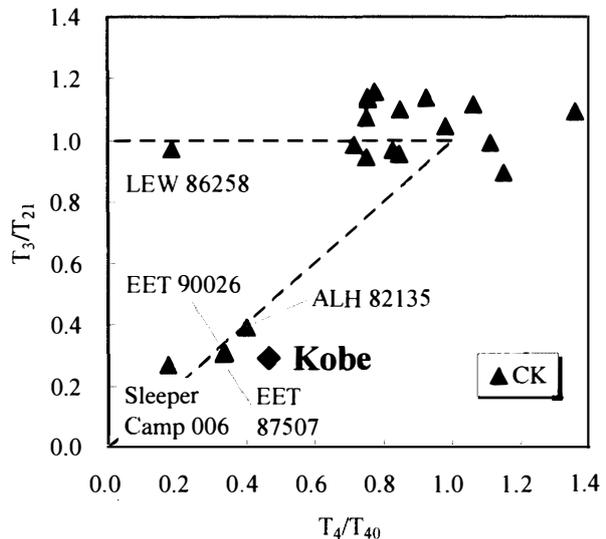


Fig. 3. A $(^3\text{He}/^{21}\text{Ne})_c$ vs. $(^{22}\text{Ne}/^{21}\text{Ne})_c$ plot (so-called Bern Plot) for CK chondrites. The solid line is a best fit for ordinary chondrite data (Nishiizumi et al., 1980). Kobe and some CK chondrites plot considerably below this line, which indicates ^3He loss. Noble gas data in this diagram, aside from Kobe data, are derived from Shima et al. (1973), Wieler et al. (1985), and Scherer and Schultz (2000).

Fig. 4. A T_3/T_{21} vs. T_4/T_{40} plot for CK chondrites. Ages were calculated using the same noble gas data as Fig. 3, with the same assumptions as used for calculating the exposure ages and gas retention ages for Kobe. The meteorites that plot along a dashed line with a slope of one have experienced loss of both $^3\text{He}_c$ and $^4\text{He}_r$, possibly during the time of exposure to cosmic-rays. This applies to Kobe, ALH 82135, Sleeper Camp 006, EET 87507, and EET 90026. Meteorites that plot along the other dashed line with a slope of zero indicate only $^4\text{He}_r$ loss before or at the time of ejection from their parent body(ies). This applies to LEW 86258.



and Bogard, 1978; Scherer et al., 1994, 1998), this is not the case for Kobe, which was recovered immediately after falling. It is possible that preferential Ar loss from Kobe occurred prior to its falling onto the Earth. However, there is another possible explanation for the shorter T_{38} age. As has recently been reported by Takaoka et al. (2000), the noble gases released from Kobe by a laser ablation method yielded concordant T_{21} and T_{38} ages in some cases, suggesting that the present results is simply

due to an inhomogeneous distribution of calcium-bearing plagioclase in the sample, as calcium is one of the major target elements for cosmogenic ^{38}Ar production. In fact, petrographic observations show that plagioclase is coarse-grained (up to $\sim 300\mu\text{m}$, Tsuchiyama, personal communication). It is likely that our sample had a relatively low concentration of calcium-bearing plagioclase. Considering that the difference in T_{38} ages may be related to differences in mineralogy of individual sample splits, the cause of the shorter T_{40} age should be regarded as being different from that responsible for the shorter T_{38} age or the loss of cosmogenic ^3He (*i.e.* solar heating during the time of cosmic-ray exposure). The substantially shorter T_{40} age may record some alternative processes, such as thermal events caused by impacts that occurred around at 2.1 billion years ago.

5. Summary

Our noble gas results from the Kobe meteorite show that it has low concentrations of primordial heavy noble gases and a high $^{129}\text{Xe}/^{132}\text{Xe}$ ratio, which are consistent with characteristics of CK meteorites reported previously by Scherer and Schultz (2000). Cosmic-ray exposure ages and gas retention ages of Kobe and some CK chondrites suggest that they have lost their He by solar heating during exposure to cosmic-rays. The shorter T_{40} inferred for Kobe might not be explained by Ar loss by a similar process, and may instead indicate thermal events that occurred about 2 billion years ago.

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References

- Alexeev, V.A. (1998): Parent bodies of L and H chondrites: Times of catastrophic events. *Meteorit. Planet. Sci.*, **33**, 145–152.
- Anders, E. (1964): Origin, age, and composition of meteorites. *Space Sci. Rev.*, **3**, 583–714.
- Anders, E. and Grevesse, N. (1989): Abundances of the elements: Meteoritic and solar. *Geochim. Cosmochim. Acta*, **53**, 197–214.
- Eberhardt, P., Eugster, O., Geiss, J. and Marti, K. (1966): Rare gas measurements in 30 stone meteorites. *Z. Naturforsch.*, **21a**, 414–426.
- Eugster, O. (1988): Cosmic-ray production rates for ^3He , ^{21}Ne , ^{38}Ar , ^{83}Kr , and ^{126}Xe in chondrites based on ^{81}Kr -Kr exposure ages. *Geochim. Cosmochim. Acta*, **52**, 1649–1662.
- Eugster, O., Michel, Th., Niedermann, S., Wang, D. and Yi, W. (1993): The record of cosmogenic, radiogenic, fissiogenic, and trapped noble gases in recently recovered Chinese and other chondrites. *Geochim. Cosmochim. Acta*, **57**, 1115–1142.
- Eugster, O., Polnau, E. and Terribilini, D. (1998): Cosmic ray- and gas retention ages of newly recovered and of unusual chondrites. *Earth Planet. Sci. Lett.*, **164**, 511–519.
- Gibson, E.K., Jr. and Bogard, D.D. (1978): Chemical alterations of the Holbrook chondrite resulting from terrestrial weathering. *Meteoritics*, **13**, 277–289.

- Graf, T. and Marti, K. (1989): Exposure ages of H-chondrites and parent body structure (abstract). *Lunar and Planetary Science XX*. Houston, Lunar Planet. Inst., 353-354.
- Graf, T. and Marti, K. (1995): Collisional history of H chondrites. *J. Geophys. Res.*, **100**, 21247-21263.
- Heymann, D. (1971): The inert gases: He, Ne, Ar, Kr and Xe (2). *Handbook of Elemental Abundances in Meteorites*, ed. by B. Mason. New York, Gordon and Breach Sci. Publishers, 29-66.
- Heymann, D. and Mazor, E. (1968): Noble gases in unequilibrated ordinary chondrites. *Geochim. Cosmochim. Acta*, **32**, 1-19.
- Hintenberger, H., Schultz, L. and Wänke, H. (1966): Messung der Diffusionsverluste von radiogenen und spallogenen Edelgasen in Steinmeteoriten II. *Z. Naturforsch.*, **21a**, 1147-1159.
- Kallemeyn, G.W., Rubin, A.E. and Wasson, J.T. (1991): The compositional classification of chondrites: V. The Karoonda (CK) group of carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **55**, 881-892.
- Kaneoka, I. (1989): Noble gas degassing from meteorites as inferred from ^{40}Ar - ^{39}Ar analytical data. *Proc. NIPR. Symp. Antarct. Meteorites*, **2**, 288-295.
- Lodders, K. and Fegley, B., Jr. (1998): *The Planetary Scientist's Companion*. New York, Oxford Univ. Press, 371 p.
- Loeken, Th., Scherer, P., Weber, H.W. and Schultz, L. (1992): Noble gases in eighteen stone meteorites. *Chem. Erde*, **52**, 249-259.
- Marti, K. (1967): Trapped xenon and the classification of chondrites. *Earth. Planet. Sci. Lett.*, **2**, 193-196.
- Mazor, E., Heymann, D. and Anders, E. (1970): Noble gases in carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **34**, 781-824.
- Nakamura, N., Ebihara, M., Hirota, Y., Oura, Y., Yoneda, K., Kojima, H., Tomeoka, K., Kojima, T., Komura, K., Clayton, R.N., Mayeda, T.K. and Wang, D. (2000a): The Kobe meteorite: Preliminary results of bulk chemical composition, petrography, cosmic-ray induced radio-activities, oxygen isotopes and classification. *Lunar and Planetary Science XXXI*. Houston, Lunar Planet. Inst., Abstract #1234 (CD-ROM).
- Nakamura, N., Kojima, H., Haramura, H., Tomeoka, K., Clayton, R.N. and Mayeda, T.K. (2000b): The Kobe meteorite: Classification and consortium studies (abstract). *Antarctic Meteorites XXV*. Tokyo, Natl Inst. Polar Res., 99-101.
- Nishiizumi, K., Regnier, S. and Marti, K. (1980): Cosmic ray exposure ages of chondrites, pre-irradiation and constancy of cosmic ray flux in the past. *Earth Planet. Sci. Lett.*, **50**, 156-170.
- Scherer, P. and Schultz, L. (2000): Noble gas record, collisional history, and pairing of CV, CO, CK, and other carbonaceous chondrites. *Meteorit. Planet. Sci.*, **35**, 145-153.
- Scherer, P., Schultz, L. and Loeken, Th. (1994): Weathering and atmospheric noble gases in chondrites. *Noble Gas Geochemistry and Cosmochemistry*, ed. by J. Matsuda. Tokyo, Terra Sci. Publ., 43-53.
- Scherer, P., Herrmann, S. and Schultz, L. (1998): Noble gases in twenty-one Saharan LL-chondrites: Exposure ages and possible pairings. *Meteorit. Planet. Sci.*, **33**, 259-265.
- Schultz, L., Weber, H.W. and Begemann, F. (1990): Planetary noble gases in H3- and H4-chondrite falls (abstract). *Meteoritics*, **25**, 405-406.
- Schultz, L., Weber, H.W. and Begemann, F. (1991): Noble gases in H-chondrites and potential differences between Antarctic and non-Antarctic meteorites. *Geochim. Cosmochim. Acta*, **55**, 59-66.
- Shima, M., Shima, M. and Hintenberger, H. (1973): Chemical composition and rare gas content of four new detected Antarctic meteorites. *Earth Planet. Sci. Lett.*, **19**, 246-249.
- Steiger, R.H. and Jäger, E. (1977): Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth. Planet. Sci. Lett.*, **36**, 359-362.
- Takaoka, N., Nakamura, T., Nagao, K. and Nakamura, N. (2000): Noble gases in the Kobe carbonaceous chondrite (abstract). *Meteorit. Planet. Sci.*, **35**, A154-A155.
- Tomeoka, K., Kojima, T., Kojima, H. and Nakamura, N. (2000): The Kobe meteorite: Petrography and mineralogy (abstract). *Antarctic Meteorites XXV*. Tokyo, Natl Inst. Polar Res., 160-162.
- Wänke, H. (1966): Meteoritenalter und verwandte Probleme der Kosmochemie. *Fortschr. Chem. Forsch.*, **7**, 322-408.
- Wieler, R., Baur, H., Graf, Th. and Signer, P. (1985): He, Ne, and Ar in Antarctic meteorites: Solar noble gases in an enstatite chondrite (abstract). *Lunar and Planetary Science XVI*. Houston, Lunar

Planet. Inst., 902–903.

Zähringer, J. (1962): Isotopie-Effekt und Häufigkeiten der Edelgase in Steinmeteoriten und auf der Erde. *Z. Naturforsch.*, **17a**, 460–471.

Zähringer, J. (1968): Rare gases in stony meteorites. *Geochim. Cosmochim. Acta*, **32**, 209–237.

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