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NOBLE GASES AND ^{81}Kr-TERRESTRIAL AGE OF ASUKA-881757 LUNAR METEORITE

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Abstract: Noble gas compositions of the Asuka-881757 lunar meteorite were determined using 10.2 and 395.3 mg specimens. This meteorite has virtually no solar type noble gases. Small amounts of trapped Ar, Kr and Xe have relative abundances similar to those of atmospheric and planetary noble gases. K-Ar age is 3.75 ± 0.35 Ga, which agrees with the ages by other methods such as U-Th-Pb, Rb-Sr and Ar-Ar. Cosmogenic isotope concentrations are the lowest among the lunar meteorites reported until now. These isotopes were produced in space by 4π geometry irradiation. The history of A-881757 based on the cosmic-ray produced stable isotopes and ^{81}Kr is as follows: It has been shielded from the cosmic ray irradiation until it was ejected from the moon 1.35 ± 0.17 Ma ago and fell on the earth 0.06 ± 0.04 Ma ago after a moon-earth transit time of 1.29 ± 0.13 Ma. These results require an ejection event for A-881757 in addition to those responsible for the other lunar meteorites.

1. Introduction

Twelve meteorites have been identified as of lunar origin till now, of which eleven were recovered in Antarctica and one in Australia. Comprehensive descriptions of the 11 lunar meteorites from Antarctica have been given by YANAI and KOJIMA (1991). According to these studies, the specimens might have come from at least seven different sites on the moon. Before the consortium study on Asuka(A)-881757 and Yamato(Y)-793169, at least three ejection events were required for the antarctic lunar meteorites based on a chronological study (EUGSTER, 1991).

A new type of lunar meteorite, A-881757 (previously called Asuka-31), weighing 442.12 g, was discovered by Japanese Antarctic Research Expedition Party on December 20, 1988. This lunar meteorite is an unbrecciated, coarse-grained gabbro retaining the original texture after its consolidation. Petrographical, mineralogical, and chemical investigations strongly indicate that this meteorite is related to the low-Ti and the very-low-Ti lunar mare basalts (YANAI, 1991; YANAI and KOJIMA, 1991). The U-Th-Pb chronological study indicates that this meteorite has been formed 3940 Ma ago (MISAWA *et al.*, 1992a). Pb-Pb, Rb-Sr, Sm-Nd and Ar-Ar methods also give similar ages (MISAWA *et al.*, 1992b; TAKAHASHI and MASUDA, 1992). K-Ar age of

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3670 Ma, cosmic-ray exposure ages of 3 and 1.3 Ma assuming 2π and 4π irradiation, respectively, and negligible amounts of solar wind noble gases have been reported for this meteorite by EUGSTER (1992).

Noble gases of lunar meteorites give various important information about the gas retention age, duration of cosmic-ray exposure on the moon and in space, shielding depth to cosmic-ray irradiation, antiquity of regolith material, terrestrial age, etc. (*e.g.*, TAKAOKA, 1987; EUGSTER and NIEDERMANN, 1988; EUGSTER *et al.*, 1989, 1991, 1992; TAKAOKA and YOSHIDA, 1992). In the framework of a consortium study on A-881757 and Y-793169, we measured the noble gas composition of A-881757 to investigate the history of this meteorite concerning residence in the lunar regolith, transit from moon to earth, and fall on the earth.

2. Experimental Procedures

The noble gas composition was first examined using a small sample (10.2 mg) by stepped heating extractions at 600, 800, 1000, 1200, 1400, and 1700°C. Each temperature was maintained for 30 min. After that, a 395.3 mg specimen was totally melted at 1700°C to measure ^{81}Kr as well as all stable noble gases. We used our VG5400 mass spectrometer that was described before (MIURA and NAGAO, 1992). An ion counting system was installed in our laboratory to obtain a higher efficiency for ion detection. The noise level of the Daly-multiplier collector system was reduced by using a low noise photomultiplier and amplifier. The detection limits of noble gas isotopes using the ion counting system were less than 1×10^{-14} and 1×10^{-15} cm^{3}STP for He and Xe isotopes, respectively. The resolving power defined as $M/\Delta M$ was adjusted to about 600, so that most hydrocarbon peaks could be separated from the noble gas isotopes. The noble gas spectra were measured in a computer-controlled peak jumping mode. The meteorite specimens wrapped with Al-foil were heated at about 150°C overnight in the side arm of the gas extraction line to reduce the adsorbed atmospheric noble gases. Hot blank levels for the heating temperature of 1700°C were 5×10^{-10}, $<2 \times 10^{-11}$, $<1 \times 10^{-9}$, $<1 \times 10^{-13}$, and $<1 \times 10^{-14}$ cm^{3}STP for ^{4}He, ^{20}Ne, ^{40}Ar, ^{84}Kr and ^{132}Xe, respectively. The extracted noble gases were purified and separated into four fractions, He-Ne, Ar, Kr, and Xe by controlling the temperatures of a charcoal trap at liquid nitrogen temperature, -60°C, and 0°C, respectively. Calibrated atmospheric noble gases were used as a standard gas to determine the sensitivities for each noble gas element and the mass discrimination correction factors. The mass discrimination for the ^{3}He/^{4}He ratio was determined with a He standard (^{3}He/^{4}He $= 1.71 \times 10^{-4}$) prepared by mixing pure ^{3}He and ^{4}He.

During the analysis of ^{81}Kr, ^{79}Br and ^{84}KrH peaks were monitored to correct ^{81}Br and ^{80}KrH when these peaks are not negligible compared with the peak height of ^{81}Kr. In the analysis of A-881757 by total melting, these interfering peaks were negligibly small. The detection limit of ^{81}Kr was about 1×10^{-15} cm^{3}STP.

3. Results and Discussion

The noble gas concentrations and isotopic ratios are presented in Tables 1 and 2.

Table 1. He, Ne and Ar concentrations and isotopic compositions of A-881757 lunar meteorite.

	^{3}He	^{4}He	$^{3}He/^{4}He$ (10^{-4})	^{20}Ne	^{21}Ne	^{22}Ne	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$	^{36}Ar	^{38}Ar	^{40}Ar	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$
Total melt using 395.3 mg													
	10.2	33000	3.086	2.62	2.33	3.00	0.8726	0.7765	1.52	1.88	16200	1.243	10690
			±.015				±.0045	±.0023				±.012	± 88
Step heating using 10.2 mg													
600°C	6.01	10600	5.669		0.20	0.77		0.26	5.35	1.01	5860	0.1894	1095
			±.050					±.03				±.0012	± 7
800°C	1.35	20000	0.675		0.46	0.72		0.64	2.25	0.445	7970	0.1979	3543
			±.010					±.06				±.0025	± 65
1000°C	0.754	13600	0.554		0.43	0.54		0.80	0.491	0.152	3070	0.309	6260
			±.011					±.08				±.022	± 550
1200°C	0.644	8780	0.733		0.72	0.87		0.83	0.766	0.819	4220	1.069	5510
			±.013					±.08				±.097	± 310
1400°C	0.338	966	3.40		0.33	0.43		0.77	0.568	0.784	2730	1.38	4800
			±.20					±.08				±.22	± 360
1700°C	0.023	13	17		0.013	0.014		(0.93)	0.388	0.266	1220	0.68	3100
			±7									±.30	±2500
Total	9.12	54000	1.69		2.15	3.34		0.64	9.81	3.48	25100	0.355	2560

Concentrations of He, Ne and Ar are given in the unit of 10^{-9} cm^{3} STP/g.

Table 2. Kr and Xe concentrations and isotopic compositions of A-881757 lunar meteorite.

	^{84}Kr	^{78}Kr	^{80}Kr	^{81}Kr	^{82}Kr	^{83}Kr	^{86}Kr	^{132}Xe	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{134}Xe	^{136}Xe
		^{84}Kr = 100							^{132}Xe = 100							
Total melt using 395.3 mg																
	22.4	2.156	9.10	0.916	24.82	26.45	29.35	10.1	1.28	2.02	9.49	98.43	16.29	84.6	43.0	38.30
		±.034	±.20	±.061	±.45	±.45	±.42		±.11	±.16	±.31	±1.84	±.47	±1.6	±1.0	±.77
Step heating using 10.2 mg																
600°C	125	0.52	4.02		20.7	19.1	30.4	8.35			8.1	107	16.0	79	41.7	33.6
		±.21	±.42		±1.2	±1.4	±1.7				±1.8	±10	±3.3	±12	±5.4	±2.3
800°C	76.1	0.41	4.10		19.4	20.3	29.8	4.47	1.9	1.4	8.1	125	17.8	88	40.7	38.2
		±.10	±.65		±1.5	±1.1	±1.3		±.9	±.7	±2.0	±19	±2.6	±8	±5.5	±5.5
1000°C	23.4	1.09	4.28		20.3	21.6	30.9	3.04			9.0	95	14.8	82	38.8	31.4
		±.41	±.84		±2.7	±2.8	±4.3				±2.8	±13	±5.7	±19	±4.5	±5.8
1200°C	23.1	1.25	5.83		21.3	21.7	31.2	8.50	1.4	1.8	10.6	95	16.2	84	42.4	36.4
		±.49	±.51		±1.9	±1.8	±3.9		±.9	±1.2	±3.4	±10	±3.2	±10	±5.0	±7.4
1400°C	15.0	1.77	6.21		23.6	22.2	30.3	3.82			10.6	109	13.7	94	39.8	37.4
		±.96	±.07		±3.5	±2.1	±3.6				±2.9	±10	±4.0	±11	±7.7	±6.7
1700°C	10.6	0.97	4.19		19.9	19.8	30.0	3.55			7.6	104	15.1	74	38.1	33.6
		±.38	±.98		±2.5	±2.3	±1.9				±2.1	± 6	±2.9	±6	±5.8	±5.2
Total	273							31.7								

^{84}Kr and ^{132}Xe are concentrations given in the unit of 10^{-12} cm^3 STP/g.

Table 3. Cosmogenic and radiogenic noble gases and cosmic-ray exposure, ^{81}Kr apparent exposure, terrestrial and K-Ar ages of A-881757.

Weight	^{3}He	^{21}Ne	^{38}Ar	^{81}Kr	^{83}Kr	^{126}Xe	T_3	T_{21}	T_{38}	T_{83}	T_{126}	T_{exp}	T_{app}	T_{terr}	^{4}He	^{40}Ar	K-Ar age
(mg)	(10^{-9} cm^3 STP/g)			(10^{-12} cm^3 STP/g)			(Ma)								(10^{-9} cm^3 STP/g)		(Ma)
395.3	10.2	2.33	1.88	0.205	1.62	0.172	0.62	1.26	1.31	≦1.37	1.1–1.4	1.29 ±.13	1.59 ±.15	0.064 ±.042	33000	16200	3750 ±350
10.2	9.1	2.15	1.78												54000	25100	

Following production rates were used: $P_3 = 16.4$, $P_{21} = 1.84$ and $P_{38} = 1.40$ (10^{-9} cm^3 STP/g/Ma), and $P_{83} \geqq 1.05$ and $P_{126} = 0.122$–0.156 (10^{-12} cm^3 STP/g/Ma).

The amounts of Ne isotopes released were so small that the corrections for $^{40}Ar^{++}$ at $M/e=20$ and for blank ^{20}Ne caused large uncertainties in determining the ^{20}Ne amount. Therefore, we do not present ^{20}Ne concentrations and $^{20}Ne/^{22}Ne$ ratios for the step heating analyses. Total concentrations of ^{3}He and ^{21}Ne by step heating are in good agreement with those by total melting, indicating a uniform distribution of cosmogenic noble gases in this meteorite. However, ^{4}He and ^{40}Ar which are mostly radiogenic show variable concentrations for the two different analyses, suggesting heterogeneous distribution of U, Th and K. Trapped Ar, Kr and Xe concentrations are also distributed heterogeneously. Kr and Xe have clear excesses in the light isotopes due to the cosmic-ray products. Enrichments in heavy Xe isotopes relative to trapped Xe are clearly present in the 395.3 mg sample.

3.1. Abundances of trapped noble gases

The Ne isotopic ratios obtained by total melting indicate virtually no trapped Ne. The low ^{3}He concentration of about 1×10^{-8} cm^{3}STP/g measured in both total melt and step heating analysis, and the very low $^{3}He/^{4}He$ ratios, $<7\times10^{-5}$, observed in 800, 1000 and 1200°C fractions of step heating can be interpreted as a short duration of cosmic-ray irradiation and negligible amounts of solar wind noble gases in this meteorite. These results are consistent with those by EUGSTER (1992). Hence, the trapped He and Ne concentrations are negligibly small and difficult to be estimated. Trapped ^{36}Ar, ^{84}Kr and ^{132}Xe concentrations obtained by total melting are 3.4, 0.21, and 0.097×10^{-10} cm^{3}STP/g, respectively, which are the lowest among those reported before for other lunar meteorites (BOGARD and JOHNSON, 1983; TAKAOKA, 1986, 1987; EUGSTER and NIEDERMANN, 1988; EUGSTER *et al.*, 1991; TAKAOKA and YOSHIDA, 1992; EUGSTER, 1992). The concentrations obtained by step heating were higher than the above values. The trapped ^{84}Kr and ^{132}Xe concentrations normalized to ^{36}Ar are

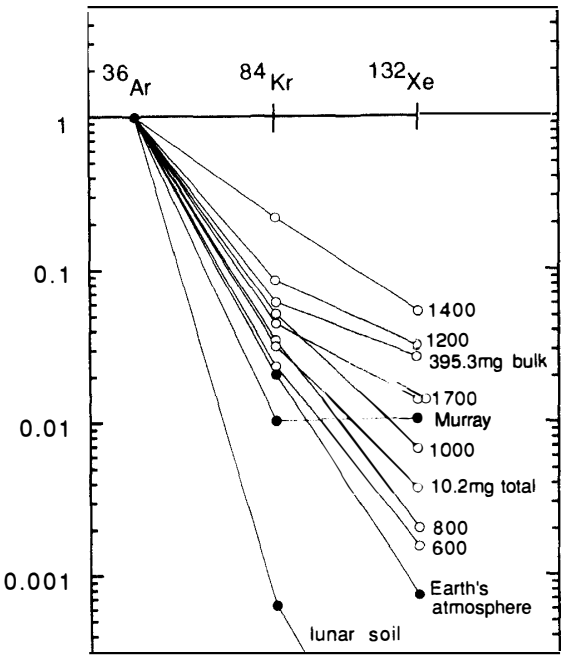

Fig. 1. *$^{84}Kr/^{36}Ar$ and $^{132}Xe/^{36}Ar$ ratios of trapped Ar, Kr and Xe are plotted. The numerical figures represent the extraction temperatures (°C) of stepped heating. The abundance ratios of solar (lunar soil 12001 ilmenite 125 μm: EBERHARDT et al., 1972), atmospheric and planetary (Murray: MAZOR et al., 1970) noble gases are presented for comparison. The abundance patters determined in this work for the A-881757 lunar meteorite plot between or above those of the atmospheric and the planetary noble gas compositions. The A-881757 shows the pattern enriched in the heavier noble gases; it is distinctly different from those for solar noble gases, indicating a negligible contribution of solar wind gases in this meteorite.*

plotted in Fig. 1. They plot between or above those of the atmospheric and planetary noble gas abundance patterns and show enrichments of Kr and Xe compared with the solar wind noble gas pattern. These results imply that this lunar meteorite contains no detectable noble gases of solar wind origin. This gabbroic lunar rock must have been buried in the deep interior of the lunar surface until ejection from the moon. As will be discussed later, during the residence in the deep interior, this meteorite was perfectly shielded from galactic cosmic-rays as well as the solar wind. The unbrecciated structure of this meteorite supports this fact.

The isotopic compositions of trapped Kr and Xe are difficult to be determined from the data obtained in this work. Irreversible adsorption of Kr and Xe of terrestrial atmospheric origin has been reported for diogenites (MICHEL *et al.*, 1990) and for lunar anorthosites (NIEDERMANN and EUGSTER, 1992). Hence, we assumed trapped Kr and Xe in A-881757 to be of atmospheric isotopic composition. Very high $^{40}Ar/^{36}Ar$ ratio of 10690, however, implies a negligible contribution of atmospheric Ar to this sample.

3.2. Radiogenic noble gases

Table 3 shows that the concentrations of both ^{4}He and ^{40}Ar are about 60% higher in the 10.2 mg specimen than in the 395.3 mg sample, probably due to higher concentrations of U, Th and K in the smaller sample compared to the larger one. Chemical heterogeneity of A-881757 has been reported by others (LINDSTROM *et al.*, 1991; FUKUOKA, 1992), which may be due to the fact that this meteorite is a coarse-grained gabbro (YANAI, 1991). For this reason, the ^{40}Ar concentration of 1.62×10^{-5} cm^{3}STP/g obtained from the larger specimen was adopted to calculate the K-Ar age using a concentration of 0.04 wt% K_2O determined by standard wet chemical analysis by H. HARAMURA (YANAI, 1991). The resulting K-Ar age is (3.75 ± 0.35) Ga assuming 10 and 20% errors for the ^{40}Ar and K contents, respectively. This age is in good agreement with the ages of 3.940 ± 0.028 Ga by Pb-Pb (MISAWA *et al.*, 1992a), 3.789 ± 0.016 Ga by Ar-Ar (MISAWA *et al.*, 1992b), and 3.67 Ga by K-Ar (EUGSTER, 1992). However, the K contents of bulk samples reported by other workers vary considerably: 0.017 wt% by LINDSTROM *et al.* (1991), 0.031 and 0.03 wt% by KOEBERL *et al.* (1992), and 0.024 and 0.032 wt% by FUKUOKA (1992). These discordant K contents increase the uncertainty in the K-Ar age calculated above.

The U and Th concentrations reported for A-881757 also vary: 0.11 and 0.09 ppm U, and 0.35 and 0.31 ppm Th (LINDSTROM *et al.*, 1991), 0.21 and 0.11 ppm U, and 0.43 and 0.42 ppm Th (KOEBERL *et al.*, 1992), and 0.09 and 0.10 ppm U, and 0.39 and 0.51 ppm Th (FUKUOKA, 1992). Whereas the U concentration of the larger specimen used in this work could be estimated from the fissiogenic ^{136}Xe concentration. Figure 2 is a plot of $^{134}Xe/^{130}Xe$ *vs.* $^{136}Xe/^{130}Xe$ ratios determined for the large size specimen after the correction for cosmogenic isotopes. This plot shows clear enrichments in ^{134}Xe and ^{136}Xe isotopes produced from the spontaneous fission of ^{238}U. The data point lies on both lines corresponding to ^{244}Pu and ^{238}U fission. However, ^{244}Pu must have been extinct and the accumulated fission Xe derived from ^{244}Pu must have been degassed when this gabbroic rock was formed at about 3.8 Ga ago determined radiometrically as noted above. The concentration of fissiogenic ^{136}Xe was calculated

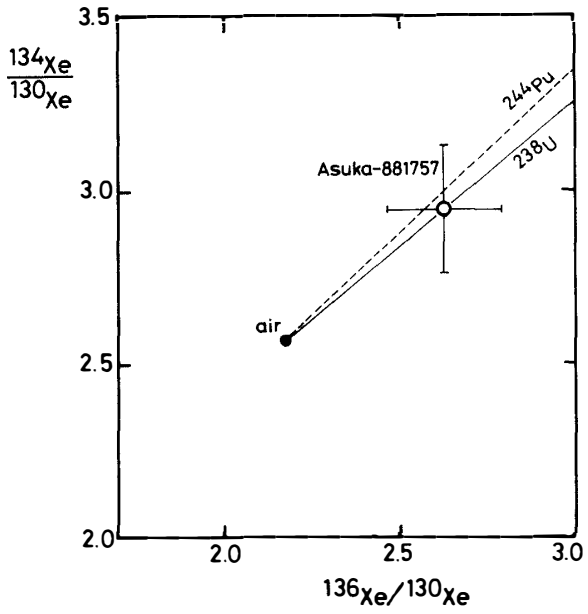

Fig. 2. A plot of $^{134}Xe/^{130}Xe$ vs. $^{136}Xe/^{130}Xe$ ratios determined for A-881757 by total melting using 395.3 mg. The ratios have been corrected for cosmogenic Xe isotopes. Because the data point lies on the mixing lines between trapped and ^{238}U fission Xe, the excess ^{134}Xe and ^{136}Xe can be attributed to the spontaneous fission of ^{238}U. If the K-Ar age of 3750 Ma is assumed for the retention time of the fissiogenic ^{136}Xe concentration of 6.6×10^{-13} cm^{3}STP/g, a U concentration of 0.26 ppm can be calculated for this specimen.

as 6.6×10^{-13} cm^{3}STP/g by subtracting trapped Xe, for which atmospheric isotopic ratios were assumed. If we assume the K-Ar age noted above as a period for fissiogenic ^{136}Xe retention, U concentration can be calculated as 0.26 ppm. In this calculation, 5.45×10^{-7} for branching ratio and 0.063 for ^{136}Xe fission yield were used (OZIMA and PODOSEK, 1983). The obtained U content of 0.26 ppm is somewhat higher than the reported values, which may be due to a heterogeneity in U distribution. ^{4}He concentration produced from U and Th decay during the K-Ar age of 3.75 Ga was calculated as 3.1×10^{-4} cm^{3}STP/g, which is about one order of magnitude higher than the observed concentration of 3.3×10^{-5} cm^{3}STP/g. Most of ^{4}He from U and Th must have been lost during the 3.8 Ga (K-Ar). He loss from this meteorite is supported by the cosmogenic ^{3}He concentration which is about half of an expected value from the cosmogenic ^{21}Ne and ^{38}Ar concentrations.

3.3. *Cosmic-ray produced noble gases and related ages*

Cosmic-ray produced noble gas concentrations are presented in Table 3. The cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar concentrations obtained by total melting agree with those from the step heating experiment. Moreover, the concentrations are in good agreement with those by EUGSTER (1992). The ^{81}Kr concentration is 2.05×10^{-13} cm^{3}STP/g, which is similar to that of eucrites (MIURA *et al.*, 1993) and lunar meteorites (EUGSTER and NIEDERMANN, 1988; MICHEL *et al.*, 1991). Cosmogenic ^{83}Kr and ^{126}Xe concentrations have been estimated on the assumption that trapped Kr and Xe are isotopically the same as those of air and that fissiogenic Kr and Xe are from ^{238}U spontaneous fission.

In order to derive the irradiation history of this meteorite by cosmic-rays, it is essential to judge whether the cosmogenic nuclides were produced in 2π or 4π geometry. The fact that there are no solar-type noble gases in this meteorite strongly suggests that the meteorite material was buried deep below the lunar surface until the

ejection event. This conclusion is supported by the ^{36}Cl, ^{26}Al, and ^{10}Be concentrations that indicate that the material resided deeper than several m below the lunar surface before the ejection (NISHIIZUMI *et al.*, 1992). Since ^{131}Xe is produced by secondary neutron capture of Ba, the ^{131}Xe concentration relative to the other cosmogenic Xe isotopes such as ^{126}Xe is an indicator for shielding depth (*e.g.*, HOHENBERG *et al.*, 1978). Cosmogenic Xe isotopes corrected for trapped and fission Xe are presented in Table 4. The $^{131}Xe/^{126}Xe$ ratio is 4.71, which is slightly higher than the values (ranging from 3.2 to 4.5) estimated for weak shielding (less than 30 g/cm^2, HOHENBERG *et al.*, 1978), assuming 98 ppm Ba and 3.4 ppm La (FUKUOKA, 1992). Since the shielding depth is estimated as more than several meters before the ejection event in a simple scenario, the meteorite was irradiated by cosmic-rays mostly in space (NISHIIZUMI *et al.*, 1992). We can expect the cosmic-ray produced $^{131}Xe/^{126}Xe$ ratio as higher than 20 during the residence buried in a deep part of the moon (>500 g/cm^2 shielding by HOHENBERG *et al.*, 1978). If most of the cosmogenic Xe of this meteorite has been produced under such a condition, the cosmogenic $^{131}Xe/^{126}Xe$ ratio should be much higher than the observed value of 4.71. Assuming the cosmogenic $^{131}Xe/^{126}Xe$ ratios of 3.5 and 20 for a free-space and a deep part of the moon, respectively, we can calculate that about 90% of the total ^{126}Xe has been produced by 4π geometry irradiation in space. From these facts, we can safely consider that most of the cosmogenic nuclides in this meteorite have been produced after the ejection from the moon. In the following discussion, we consider all cosmogenic nuclides as products of 4π geometry irradiation in space.

To calculate cosmic-ray exposure ages, production rates by EUGSTER (1988) were used after correcting for the chemical compositions. The concentrations of target nuclides were taken from YANAI (1991), LINDSTROM *et al.* (1991), FUKUOKA (1992), and KOEBERL *et al.* (1992). Since the shielding depth to cosmic-ray irradiation in space is not known for our sample, we adopt an average meteoritical shielding corresponding to a cosmogenic ratio $^{22}Ne/^{21}Ne=1.11$. Cosmic-ray exposure ages calculated by ^{21}Ne, ^{38}Ar, ^{83}Kr and ^{126}Xe are in the range from 1.26 to 1.41 Ma (Table 3). The short age of 0.62 Ma obtained from ^{3}He is probably caused by a loss of He from the meteorite. The ages T_{21} and T_{38} are 1.26 and 1.31 Ma, respectively. The ages T_{83} and T_{126} are similar to the above ages, but they have relatively large uncertainties because the target element concentrations reported by different workers vary considerably. So, we adopted an average value of 1.29 Ma calculated from T_{21} and T_{38} as the cosmic-ray exposure age, T_{exp}, with a 10 % error considering the uncertainties in the production rates and the concentrations of cosmogenic Ne and Ar.

The ^{81}Kr-terrestrial age T_{terr} can be calculated by the following equation (FREUNDEL *et al.*, 1986),

$$T_{terr}=(1/\lambda)\ln(T_{app}/T_{exp}),$$

where T_{app} is an apparent exposure age based on the cosmogenic Kr isotopic compositions (Table 4).

The apparent exposure age was calculated by,

$$T_{app}=(1/\lambda)(P_{81}/P_{83})(^{83}Kr/^{81}Kr)_c,$$

Table 4. Cosmogenic Kr and Xe isotopic compositions and concentrations of A-881757.

^{83}Kr	^{78}Kr	^{80}Kr	^{81}Kr	^{82}Kr	^{84}Kr	^{126}Xe	^{124}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe
	^{83}Kr = 100						^{126}Xe = 100				
1.62	21.8 ±1.4	73.7 ±5.5	12.7 ±1.1	76 ±10	63 ±33	0.172	55.2 ±8.2	153 ±23	210 ±110	99 ±29	471 ±45

^{83}Kr and ^{126}Xe are concentrations in the unit of 10^{-12} cm^3 STP/g.

where λ ($=3.25\times10^{-6}$ y^{-1}) is the decay constant of ^{81}Kr (EASTWOOD *et al.*, 1964) and P_m means a production rate for ^{m}Kr. The apparent exposure ages T_{app} of 1.73 ± 0.24 and 1.59 ± 0.15 Ma were obtained using the ^{80}Kr/^{83}Kr and ^{82}Kr/^{83}Kr, and ^{78}Kr/^{83}Kr ratios, respectively (MARTI, 1967; MARTI and LUGMAIR, 1971; FINKEL *et al.*, 1978). Although the ages agree with each other within the experimental errors, the former value might have been affected by ^{80}Kr and ^{82}Kr produced from neutron capture of Br or by ^{40}Ar charge transfer reaction in the flight tube of mass spectrometer. From this reason the latter value was adopted to calculate the ^{81}Kr terrestrial age T_{terr} using the above formula.

The resulting terrestrial age T_{terr} is 0.064 ± 0.042 Ma assuming a 10% error for the cosmic-ray exposure age T_{exp}. The sum of the exposure age T_{exp} and of the terrestrial age T_{terr} is 1.35 ± 0.17 Ma which is the time when this meteorite was ejected from the moon.

If this meteorite was excavated from a place deeper than several meters, the exposure and terrestrial ages calculated based on cosmogenic ^{36}Cl, ^{26}Al and ^{10}Be are 0.9 ± 0.1 Ma and less than 0.05 Ma, respectively (NISHIIZUMI *et al.*, 1992). The ages obtained in this work are somewhat longer than those estimated by NISHIIZUMI *et al.* (1992).

3.4 History of A-881757 and comparison with other lunar meteorites

The K-Ar, cosmic-ray exposure, and terrestrial ages as well as trapped noble gas concentrations obtained in this work yield the following history of the A-881757 lunar meteorite. This gabbroic rock solidified 3.75 ± 0.35 Ga ago and resided deep below the lunar surface where it was exposed neither to galactic cosmic rays nor to solar wind particles until 1.35 ± 0.17 Ma ago. An impact of an asteroid or comet on a mare area of the moon ejected A-881757 which arrived on earth 0.064 ± 0.042 Ma ago after a moon-earth transit time of 1.29 ± 0.13 Ma.

The short terrestrial age is in the range of ages reported for other lunar meteorites. However, the duration of cosmic-ray exposure in space of 1.3 Ma is one order of magnitude longer than that for the other lunar meteorites EET87521 (EUGSTER, 1992), Y-793274 (NISHIIZUMI *et al.*, 1991a; EUGSTER *et al.*, 1992), MAC88104/5 (EUGSTER *et al.*, 1991; NISHIIZUMI *et al.*, 1991b; VOGT *et al.*, 1991), Y-791197 (NISHIIZUMI *et al.*, 1991b; VOGT *et al.*, 1991) and ALHA81005 (NISHIIZUMI *et al.*, 1991b) except for the paired lunar meteorites Y-82192/3 and Y-86032 (moon-earth transit time of about 10 Ma, TAKAOKA, 1987; EUGSTER and NIEDERMANN, 1988;

TAKAOKA and YOSHIDA, 1992). We, thus, conclude that the A-881757 lunar meteorite originates from a distinctly different ejection event on the moon that occurred about 1.3 Ma ago. This is an additional ejection event to at least three events responsible for the lunar meteorites proposed by EUGSTER (1991).

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