Proc. NIPR Symp. Antarct. Meteorites, 2, 25–35, 1989

PRELIMINARY REPORT ON THE YAMATO-86032 LUNAR METEORITE: III. AGES, NOBLE GAS ISOTOPES, OXYGEN ISOTOPES AND CHEMICAL ABUNDANCES

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Abstract: The isotope abundances of He, Ne, Ar, Kr, and Xe, including ^{81}Kr, the oxygen isotopic composition, and the concentrations of Na, K, Sc, Ti, Cr, Fe, Co, Y, Zr, La, Sm, Eu, Hf, Ta, and W were determined for the lunar meteorite Yamato-86032. Based on the radionuclide ^{81}Kr we obtain a terrestrial age of 72000 ± 30000 years, whereas the cosmic-ray exposure age is 10.6 ± 0.6 Ma assuming exposure of the meteorite as a small object in space. Exposure to cosmic rays occurred at shallow shielding of about 40 g/cm^2. The K-Ar gas retention ages of two separate splits are 3680 ± 300 Ma and 3810 ± 400 Ma, respectively. All ages agree with those for the lunar meteorites Y-82192 and Y-82193 recovered in the same area on the antarctic ice. The small amounts of trapped solar wind noble gases indicate that the Y-86032 material was exposed only briefly, some grains perhaps not at all, to the solar wind. The concentrations are similar to those of the Yamato-82 lunar meteorites. The oxygen isotopic composition is within the range of that for lunar rocks. The chemical composition of the samples from Y-86032, Y-82192, and Y-82193 is uniform for most major elements but not for all minor and trace elements, probably due to inhomogeneity of the source material. From the fact that the history of Y-86032 is the same as that of Y-82192/3 we conclude that these three rocks are pieces of the same meteorite fall.

1. Introduction

In this paper we report the results on lunar meteorite Yamato-86032 obtained so far for the investigation of the noble gas isotopic abundances, of the oxygen isotopic composition, and of the concentrations of the elements relevant for the interpretation of the noble gases.

Sample split Y-86032,86 was allocated to the University of Bern for noble gas isotopic analyses, determination of the cosmic-ray exposure age and terrestrial age and for chemical analyses. Additional noble gas analyses were performed at the Max-Planck-Institute for Chemistry in Mainz using a bulk sample from split Y-86032,89. Preliminary results for Y-86032 have been reported by EUGSTER (1988) and EUGSTER and NIEDERMANN (1988a).

Also included in this report are the oxygen isotopic analyses carried out at the University of Chicago.

2. Experimental Procedure and Results

Sample split Y-86032,86 (0.420 g) was crushed in a stainless steel mortar to a grain size $<700\ \mu m$. Two bulk samples of 1 mg each were analyzed as pilot samples for a first characterization of the He, Ne, and Ar isotope abundances followed by a bulk sample of 20.3 mg. A sample of about 240 mg was separated into two grain size fractions ($>30\ \mu m$ and $<30\ \mu m$) by sedimentation in acetone taking advantage of the difference in sedimentation speed. This was done to study the question whether trapped solar wind noble gases are enriched on the breccia grain surfaces. For chemical analyses a bulk sample of 40.7 mg was consumed. The remaining bulk material will be used for Kr isotope analysis by resonance ionization mass spectrometry and for radionuclide analyses. From split Y-86032,89 a bulk sample of 10.7 mg was used for noble gas work in Mainz.

2.1. Noble gases

The noble gases studied in Bern were analyzed in two different mass spectrometer systems. In system A two sector-type 60-degree mass spectrometers with glass tubes were used. The spectrometer employed for the He, Ne, and Ar analyses is equipped with a Faraday collector whereas the Kr/Xe spectrometer is additionally equipped with a secondary electron multiplier. System B consists of another gas extraction line and two metal-tube mass spectrometers equipped with secondary electron multi-

Table 1. Results of He, Ne, and Ar measurements of samples from meteorite Yamato-86032.

Sample (MS system A/B)	Weight	^{3}He	^{22}Ne	^{36}Ar	$\frac{^{4}He}{^{3}He}$	$\frac{^{20}Ne}{^{22}Ne}$	$\frac{^{21}Ne}{^{22}Ne}$	$\frac{^{38}Ar}{^{36}Ar}$	$\frac{^{40}Ar}{^{36}Ar}$
		10^{-8} cm^3 STP/g							
Y-86032,86									
Bulk (B)	0.00100 g	5.0 ±0.5	3.1 ±0.3	16.1 ±1.5	6.6 ±2.0	2.94 ±0.10	0.667 ±0.020	0.308 ±0.030	42.2 ±10.0
Bulk (B)	0.00101 g	5.7 ±0.5	4.4 ±0.3	32.6 ±2.0	6.7 ±2.0	4.85 ±0.15	0.505 ±0.020	0.247 ±0.020	28.9 ±6.0
Bulk (B)	0.02029 g	7.1 ±0.4	4.2 ±0.3	23.6 ±1.5	5.7 ±0.1	4.28 ±0.10	0.562 ±0.015	0.272 ±0.010	40.3 ±2.0
$>30\ \mu m$ (A)	0.1861 g	7.1 ±0.2	4.0 ±0.2	26.9 ±1.5	—	4.23 ±0.20	0.559 ±0.010	0.276 ±0.020	39.3 ±1.0
$>30\ \mu m$ (B)	0.02056 g	7.2 ±0.4	4.6 ±0.3	25.7 ±1.5	6.0 ±0.1	5.02 ±0.10	0.513 ±0.015	0.267 ±0.010	38.4 ±2.0
$>30\ \mu m$ (B)	0.01226 g	6.9 ±0.4	4.2 ±0.3	25.1 ±1.5	6.5 ±0.1	4.31 ±0.10	0.562 ±0.015	0.272 ±0.010	39.8 ±2.0
$<30\ \mu m$ (A)	0.00971 g	—	1.6 ±0.8	22.7 ±3.0	—	5.5 ±2.0	—	0.300 ±0.010	46.9 ±5.0
$<30\ \mu m$ (B)	0.00386 g	4.0 ±0.4	2.8 ±0.3	16.6 ±1.5	49.6 ±3.0	3.32 ±0.10	0.621 ±0.020	0.291 ±0.010	44.6 ±3.0
Y-86032,89									
Bulk	0.01067 g	5.62 ±0.60	3.22 ±0.30	5.87 ±0.60	6.00 ±0.25	1.17 ±0.02	0.780 ±0.015	0.468 ±0.020	132.2 ±5.0

Table 2. Results of Kr measurements of samples from meteorite Yamato-86032.

Sample (MS system A/B)	^{86}Kr 10^{-12} cm^3 STP/g	$^{78}Kr/^{86}Kr$	$^{80}Kr/^{86}Kr$	$^{81}Kr/^{86}Kr$	$^{82}Kr/^{86}Kr$	$^{83}Kr/^{86}Kr$	$^{84}Kr/^{86}Kr$
86032,86>30 μm (A) 0.1861 g	48.4 ±10.0	0.0667 ±0.0010	0.292 ±0.003	0.00388 ±0.00020	0.874 ±0.013	0.921 ±0.015	3.43 ±0.05
86032,86<30 μm (A) 0.00971 g	127 ±33	—	0.26 ±0.04	—	0.727 ±0.020	0.745 ±0.020	3.25 ±0.03
86032,89 Bulk 0.01067 g	47 ±8	—	—	—	—	—	—

Table 3. Results of Xe measurements of samples from meteorite Yamato-86032,86.

Sample (MS system A/B)	^{132}Xe 10^{-12} cm^3 STP/g	$^{124}Xe/^{132}Xe$	$^{126}Xe/^{132}Xe$	$^{128}Xe/^{132}Xe$	$^{129}Xe/^{132}Xe$	$^{130}Xe/^{132}Xe$	$^{131}Xe/^{132}Xe$	$^{134}Xe/^{132}Xe$	$^{136}Xe/^{132}Xe$
>30 μm (A) 0.1861 g	30.8 ±6.0	0.0126 ±0.0012	0.0183 ±0.0020	0.105 ±0.020	1.023 ±0.010	0.166 ±0.002	0.816 ±0.005	0.394 ±0.010	0.341 ±0.015
<30 μm (A) 0.00971 g	113 ±30	0.0062 ±0.0020	0.0082 ±0.0010	0.088 ±0.010	1.002 ±0.010	0.172 ±0.010	0.778 ±0.015	0.403 ±0.010	0.351 ±0.010

pliers, one mass spectrometer for He and Ne, and the other one for Ar analyses. The extraction procedure and details of the mass spectrometric technique employed at Mainz were as described previously (BEGEMANN *et al.*, 1985).

The analytical results obtained in Bern and Mainz are given in Tables 1, 2, and 3. All errors correspond to a 95% confidence level. Because relatively large samples are required for the heavy noble gases only two samples were analyzed for Kr and Xe isotopes.

2.2. *Chemical analyses*

The bulk sample of 40.7 mg was irradiated in a suprasil quartz vial for two days at 5×10^{13} n cm^{-2} s^{-1}. Two thirds of the irradiated material was dissolved by HF and $HClO_4$ in the presence of carriers of the interesting elements. By RNAA the target elements for Kr production by spallation, Y and Zr, and the only rarely determined elements Ti, Hf, Ta, and W were measured. A description of the chemical procedure is given in KRÄHENBÜHL and BURGER (1989). The remaining third of the irradiated material was used for the determination of the elements Na, K, Sc, Cr, Fe, Co, La, Sm, and Eu by INAA. Results are given in Table 4. One sigma errors for all elements but Y and Ti are ±5–10%. For Y and Ti errors amount to ±10–15%. The concentrations in the case of INAA were calculated relative to those in the reference sample IAEA soil-5 and in USGS standard BHVO-1. For most elements our data agree with those reported by KOEBERL (1988a) and by WARREN and KALLEMEYN (1988).

Table 4a. Major and minor element concentrations (weight %) of meteorite Yamato-86032.

Sample	Na	Mg	Al	Si	K	Ca	Ti	Cr	Fe	Ref.
Y-86032, 86 bulk	0.29				0.0141		0.060	0.071	2.9	this work
Y-86032, 84 impact melt	0.32				0.0135			0.066	3.20	(1)
Y-86032, 78 bulk	0.33	3.35	14.7	21.1	0.0209	11.2	0.12	0.067	3.28	(2)
For comparison										
Y-82192 bulk or matrix	0.265	2.70	13.4		0.015	10.2	0.13	0.0701	3.20	(3)
	−0.362	−3.47	−14.3		−0.0183	−10.8	−0.25	−0.102	−4.85	
Y-82193 matrix	0.30	3.06	13.6		0.0307	11.9	0.162	0.105	4.39	(4)

Table 4b. Trace element concentrations (ppm) of meteorite Yamato-86032.

Sample	Sc	Co	Rb	Sr	Y	Zr	Ba	La	Sm	Eu	Hf	Ta	W	Th	U	Ref.
Y-86032, 86 bulk	7.3	13.1			4.6	17		1.1	0.63	1.00	0.24	0.10	0.47			this work
Y-86032, 84 impact melt	7.26	13.2	<10	118		25	30	1.0	0.52	0.722	0.54	0.07	0.3	0.22	0.07	(1)
Y-86032, 78 bulk	8.0	14.5					36	1.6	0.66	1.04	0.49			0.23	0.062	(2)
For comparison																
Y-82192 bulk or	8.23	13.0	0.39	136		24	20	1.06	0.534	0.754	0.36	0.038		0.1	0.031	(3)
matrix	−14.5	−19.9	−3.0	−190		−37	−32.56	−1.54	−0.68	−0.94	−0.92	−0.060		−0.23	−0.066	
Y-82193 matrix	12.2			180			28	1.27	0.65	0.82	0.45	0.034		0.20	0.04	(4)

References: (1) KOEBERL (1988c); (2) WARREN and KALLEMEYN (1988); (3) Range for data given by BISCHOFF *et al.* (1987), FUKUOKA *et al.* (1986), KOEBERL (1988b), LINDSTROM *et al.* (1987), TAKAHASHI and MASUDA (1987), and WARREN and KALLEMEYN (1987); (4) FUKUOKA *et al.* (1986) preliminary data.

3. Trapped, Cosmogenic, and Radiogenic Noble Gases, Oxygen Isotopes, and Chemical Abundances

3.1. Assumptions for the partitioning of the noble gas components

The assumptions for the partitioning of the cosmogenic (c), trapped (tr) and radiogenic (r) components are the same as those for Y-82192/3 (EUGSTER and NIEDERMANN, 1988b): $(^4He/^3He)_c=5$, $^3He_{tr}=0$, $(^{20}Ne/^{22}Ne)_{tr}=12.0$, $(^{21}Ne/^{22}Ne)_{tr}=0.032$, $(^{20}Ne/^{21}Ne)_c=1.0$, $(^{36}Ar/^{38}Ar)_{tr}=5.32$, $(^{40}Ar/^{36}Ar)_{tr}=12.1$, $(^{36}Ar/^{38}Ar)_c=0.65$, and $(^{40}Ar/^{38}Ar)_c=0.2$. The isotopic composition of trapped Kr and Xe was assumed to be identical to that of terrestrial air. Furthermore, $(^{86}Kr/^{83}Kr)_c=0.015$, $(^{132}Xe/^{126}Xe)_c=0.5$, $(^{134}Xe/^{126}Xe)_c=0.05$, and $(^{136}Xe/^{126}Xe)_c=0.015$ were adopted.

3.2. Trapped noble gases

Table 5 gives the trapped noble gas component. Inspection of the He data in Table 1 shows that the measured ^4He concentration in units of 10^{-8} cm^3 STP/g is between 33 and 45 except for the <30 μm (B) sample that yielded 198. After subtraction of ^4He_c, an amount of ^4He of 5–10 remains except for the <30 μm (B) sample for which 178 is left over. Assuming that ^4He_r is $\leqq 10$ (upper limit of ^4He_r as derived for the bulk samples) we obtain for the <30 μm (B) sample a $^4He_{tr}$ content of 168.

Trapped Ne and Ar are present in all samples. The elemental pattern of trapped He, Ne, and Ar is similar to that of the trapped solar wind noble gases in lunar soil. The ratio $(^{20}Ne/^{22}Ne)_{tr}$ derived from a $^{20}Ne/^{22}Ne$ *versus* $^{21}Ne/^{22}Ne$ correlation is about 12 which is close to the typical value for trapped solar wind Ne in lunar material. Thus, we conclude that trapped He, Ne, and Ar are implanted solar wind particles with the usual addition of retrapped lunar ^{40}Ar. The origin of trapped Kr and Xe, however, is not clear. As observed before for lunar meteorites, anorthite grains con-

Table 5. Trapped noble gases in Yamato-86032.

Sample		^4He	^{20}Ne	^{36}Ar	^{86}Kr	^{132}Xe
		10^{-8} cm^3 STP/g			10^{-12} cm^3 STP/g	
Y-86032, 86						
Bulk (B)	0.00100 g	bd	7.2±0.7	14.7±1.5	na	na
Bulk (B)	0.00101 g	bd	19.3±1.5	31.2±2.0	na	na
Bulk (B)	0.02029 g	bd	15.6±1.0	22.1±1.5	na	na
>30 μm (A)	0.1861 g	bd	14.9±0.8	25.2±1.5	48±10	30±6
>30 μm (B)	0.02056 g	bd	20.7±1.5	24.2±1.5	na	na
>30 μm (B)	0.01226 g	bd	15.8±1.0	23.5±1.5	na	na
<30 μm (A)	0.00971 g	bd	7.1±4.0	20.8±3.0	127[1]±30	113[1]±30
<30 μm (B)	0.00386 g	168[2]±20	7.6±1.0	15.3±1.5	na	na
Y-86032, 89						
Bulk	0.01067 g	bd	1.2±0.2	4.65±0.50	47±8	na
For comparison						
Y-82192, 82[3] >25 μm		—	10.3	8.9	32.6	25.1
Y-82193, 100[3] >25 μm		—	24	19.3	39.2	31.6

[1] Appears to be partly terrestrial contamination; [2] Obtained from total amount of ^4He after subtraction of radiogenic and cosmogenic ^4He (see text); [3] EUGSTER and NIEDERMANN (1988b); bd—below detection limit; na—not analyzed.

tain a surface adsorbed component of terrestrial atmospheric Kr and Xe (EUGSTER and NIEDERMANN, 1988b). This contamination is clearly observed for the <30 μm (A) sample for which trapped Kr and Xe are enhanced relative to trapped Ne and Ar (Table 5). Whether trapped Kr and Xe in the >30 μm (A) sample are a terrestrial contamination, solar wind or indigenous lunar gases cannot be decided from our data. The variation of the trapped gas concentrations indicate that this component is distributed quite inhomogeneously in Y-86032. The average amounts are similar to those observed in Y-82192 (BISCHOFF *et al.*, 1987; TAKAOKA, 1987; EUGSTER and NIEDERMANN, 1988b), and in Y-82193 (EUGSTER and NIEDERMANN, 1988b). These three meteorites contain about three orders of magnitude less solar wind derived noble gases than a typical lunar regolith breccia and than the lunar meteorites ALHA-81005 and Yamato-791197.

The $(^{40}Ar/^{36}Ar)_{tr}$ ratio can be derived from a $^{40}Ar/^{36}Ar$ *versus* $1/^{36}Ar$-diagram, Ar being corrected for the cosmogenic component. We obtain for the samples of Y-86032 a $^{40}Ar/^{36}Ar$ trapped ratio of 12.1 ± 3.0. For comparison, the 74001 glasses from Apollo 17 Shorty crater yield a $(^{40}Ar/^{36}Ar)_{tr}$ ratio of 8–10. They acquired their Ar when they were formed 3700 Ma ago (EUGSTER *et al.*, 1980). A $(^{40}Ar/^{36}Ar)_{tr}$ ratio of 12.1 for Y-86032 indicates that Ar was trapped about 4000 Ma ago when ^{40}K (half life 1280 Ma) was more abundant, resulting in a higher $^{40}Ar/^{36}Ar$ ratio in the lunar atmosphere. This time may be the breccia formation age; it is consistent with the K-Ar gas retention ages given in Table 9 for the two Y-86032 splits.

3.3. *Cosmogenic noble gases and production rates*

Tables 6–8 give the cosmogenic and radiogenic components. The bulk- and >30 μm samples contain quite uniform concentrations of $^{21}Ne_c$ and $^{38}Ar_c$, whereas the fine grains of the <30 μm fractions may have partially lost cosmogenic gases by diffusion. For the calculation of the cosmic-ray exposure ages we have to adopt production rates which depend on the target element concentrations, the shielding depth, and the exposure geometry (2π or 4π). Table 4 shows that for Y-86032 the abundances of the elements relevant for noble gas production are similar to those for Y-82192/3. Based on these target element abundances REEDY (pers. commun., 1988) derived noble gas production rates for 4π exposure. In particular, we conclude from REEDY's data that Y-86032,86 was exposed to cosmic rays at relatively shallow shielding: for production in the center of a sphere with 40 g/cm^2 radius the calculated ratio $(^{22}Ne/^{21}Ne)_c$ is 1.28 and $(^{131}Xe/^{126}Xe)_c$ is 2.40. These ratios are close to the measured ones of 1.25 ± 0.02 and 2.64 ± 0.50, respectively. Similar cosmogenic ratios were obtained for the Y-82192/3 meteorites. Therefore, we adopted the same 4π-production rates for Y-86032 as for Y-82192/3 (P^{21} and P^{38} in units of 10^{-8} cm^3 STP/g per Ma, P^{83} and P^{126} in 10^{-12} cm^3 STP/g per Ma): $P^{21}=0.212$, $P^{38}=0.196$, $P^{83}=1.28$, $P^{126}=0.047$ (EUGSTER and NIEDERMANN, 1988b).

3.4. *Cosmic ray exposure ages*

Based on these production rates the cosmic-ray exposure ages T^{21}, T^{38}, T^{83}, and T^{126} were calculated and are given in Table 9. As usually observed for lunar material,

Table 6. Cosmogenic and radiogenic He, Ne, and Ar in Yamato-86032.

Sample	Cosmogenic				Radiogenic
	^{3}He	^{21}Ne	^{38}Ar	$^{22}Ne/^{21}Ne$	^{40}Ar
	10^{-8} cm^3 STP/g				10^{-8} cm^3 STP/g
Y-86032, 86					
Bulk (B) 0.00100 g	5.0±0.5	2.08±0.20	2.2±0.3	1.23±0.03	501±60
Bulk (B) 0.00101 g	5.7±0.5	2.24±0.20	2.2±0.3	1.29±0.03	564±60
Bulk (B) 0.02029 g	7.1±0.4	2.31±0.12	2.3±0.2	1.25±0.02	684±70
>30 μm (A) 0.1861 g	7.1±0.2	2.22±0.12	2.7±0.2	1.26±0.02	752±80
>30 μm (B) 0.02056 g	7.1±0.4	2.30±0.12	2.3±0.2	1.25±0.02	694±70
>30 μm (B) 0.01226 g	6.9±0.4	2.32±0.12	2.4±0.2	1.24±0.02	715±70
<30 μm (A) 0.00971 g	—	—	2.9±0.4	—	813±80
<30 μm (B) 0.00386 g	4.0±0.4	1.74±0.20	2.0±0.3	1.26±0.02	555±60
Average (bulk, >30 μm)	6.5±0.8	2.24±0.10	2.35±0.20	1.25±0.02	660±100
Y-86032, 89					
Bulk 0.01067 g	5.62±0.60	2.51±0.25	1.88±0.15	1.24±0.02	720±70

Table 7. Cosmic-ray-produced Kr in meteorite Y-86032.

Sample	^{81}Kr	^{83}Kr	$^{78}Kr/^{83}Kr$	$^{80}Kr/^{83}Kr$	$^{81}Kr/^{83}Kr$	$^{82}Kr/^{83}Kr$	$^{84}Kr/^{83}Kr$
	10^{-12} cm^3 STP/g						
Y-86032, 86 >30 μm	0.188 ±0.040	12.8 ±2.5	0.177 ±0.005	0.62 ±0.03	0.0147 ±0.0008	0.82 ±0.04	0.66 ±0.20

Table 8. Cosmic-ray-produced and fission Xe in meteorite Y-86032.

Sample	Cosmogenic						Fission[1]
	^{126}Xe	$^{124}Xe/^{126}Xe$	$^{128}Xe/^{126}Xe$	$^{129}Xe/^{126}Xe$	$^{130}Xe/^{126}Xe$	$^{131}Xe/^{126}Xe$	^{136}Xe
	10^{-12} cm^3 STP/g						10^{-12} cm^3 STP/g
Y-86032, 86 >30 μm	0.47 ±0.10	0.61 ±0.10	2.4 ±0.4	4.1 ±0.8	1.2 ±0.2	2.64 ±0.50	0.56 ±0.40

[1] From spontaneous fission of ^{238}U and ^{244}Pu.

^{3}He suffered severe diffusion loss and is unsuitable for an exposure age calculation. In meteorites whose terrestrial age is not negligibly brief relative to the mean life τ^{81} of ^{81}Kr (307000 years) the apparent ^{81}Kr-Kr age $T^{81}=\tau^{81}(P^{81}/P^{83})$ $(^{83}Kr/^{81}Kr)_c$ must be higher than the exposure ages derived from stable noble gas isotopes and the respective production rate, because some ^{81}Kr decayed since the meteorite fell on Earth, resulting in an increase of T^{81} relative to $T^{av(stable)}$. As can be judged from Table 9, this is indeed the case. We obtain $T^{81}=13.4\pm1.0$ Ma and $T^{av(stable)}=10.6\pm0.6$ Ma,

Table 9. Cosmic-ray exposure ages for 4π exposure, terrestrial ages, and K-Ar ages of lunar meteorites.

Meteorite	Apparent ^{81}Kr-Kr age (T^{81}) [Ma]	T^{21}	T^{38}	T^{83}	T^{126}	$T^{av(stable)}$	Terrestrial age (T_{terr}) [years]	K-Ar age [Ma]
		[Ma]						
Y-86032, 86	13.4 ±1.0	10.6	12.0	10.0	9.9	10.6 ±0.6	72000 ±30000	3680 ±300
Y-86032, 89	—	11.8	9.6	—	—	10.7 ±1.0	—	3810 ±400
For comparison								
Y-82192, 82[1]	13.9 ±1.5	10.3	12.0	9.2	10.9	10.6 ±0.6	83000 ±35000	3900 ±200
Y-82192, 75[2]	—	9.7	12.2	—	—	11.0	—	—
Y-82192, 63C[3]	—	9.7	9.9	7.0	22.0	12.2	—	—
Y-82192, 64A[3]	—	7.5	8.6	—	—	8.0	—	—
Y-82193, 100[1]	13.9 ±1.0	10.8	12.8	9.3	10.2	10.8 ±0.7	75000 ±30000	>3000

[1] EUGSTER and NIEDERMANN (1988b), [2] BISCHOFF *et al.* (1987), [3] TAKAOKA (1987).

both ages within error limits equal to those for Y-82192 (11.0 Ma, BISCHOFF *et al.*, 1987; 8.0, and 12.2 Ma, TAKAOKA, 1987; 10.6 Ma, EUGSTER and NIEDERMANN, 1988b) and Y-82193 (10.8 Ma, EUGSTER and NIEDERMANN, 1988b). Whether this total cosmic-ray exposure indeed occurred in 4π- (as a small object in free space) or 2π-geometry (on the lunar surface) can be judged based on the ^{53}Mn activity. Preliminary ^{53}Mn data were reported by NISHIIZUMI *et al.* (1988) for lunar meteorites ALHA-81005, Y-791197, Y-82192, and Y-82193. The Moon-Earth transportation time for ALHA-81005 was probably less than 10^5 years. Thus, its ^{53}Mn activity (^{53}Mn half life$=3.7\times10^6$ years) corresponds to that for a 2π-exposure on the moon and was not significantly enhanced during the very brief travel time in space. For ALHA-81005 NISHIIZUMI *et al.* observed 176±12 dpm/kg Fe, whereas Y-82192 and Y-82193 yielded 358±21 and 311±21 dpm/kg Fe, respectively. The meteoritic activity (4π) of ^{53}Mn at low shielding (~10 g/cm^2) as observed in the St. Severin and Keyes chondrites is about 400 dpm/kg Fe (ENGLERT and HERR, 1980; HERPERS and ENGLERT, 1983), whereas for lunar cores (2π) REEDY *et al.* (1983) calculate an activity of about 200 dpm/kg Fe at low shielding. In some lunar cores higher activities were measured resulting from varying degrees of disturbance (gardening). Obviously the ^{53}Mn activity of Y-82192/3 indicates that these two stones experienced exposure to cosmic rays mainly, if not totally, in free space at 4π-exposure. In view of the Monte Carlo calculations of the transfer times of meteorites from the Moon to Earth performed by WETHERILL (1968) a 4π exposure age of about 10 Ma is rather long but cannot be excluded.

3.5. Terrestrial age

The time since Y-86032 fell on Earth is calculated from $T_{terr}=\tau^{81}\ln(T^{81}/T^{av(stable)})$. For Y-86032 we obtain $T_{terr}=72000\pm30000$ years, indistinguishable from the terrestrial ages of Y-82192 and Y-82193.

Table 10. Oxygen isotopic composition of lunar meteorite Yamato-86032.

Sample	$\delta^{17}O$ (per mill)	$\delta^{18}O$ (per mill)
Y-86032	3.03	5.64
For comparison: Apollo-16 lunar rock material		
60015, 75 anorthosite	2.93	5.59
60015, 58 glass	2.97	5.55

3.6. ^{40}Ar gas retention age

Based on the concentration of radiogenic ^{40}Ar (Table 6) and a K concentration of 141 ppm obtained from an aliquot sample (Table 4) we obtain ^{40}Ar retention ages of 3680 ± 300 Ma for split Y-86032,86 and 3810 ± 400 Ma for split Y-86032,89 (Table 9). This is the same age within experimental error limits as that for Y-82192.

3.7. Oxygen isotopic composition

The results of the oxygen isotopic analyses obtained at the University of Chicago are given in Table 10. They are compared with those observed for the cataclastic anorthosite 60015 from the Apollo-16 mission. Anorthositic material as well as a sample from the glass coating of this rock yield essentially the same $\delta^{17}O$- and $\delta^{18}O$-values as lunar meteorite Y-86032 confirming its lunar origin.

3.8. Chemical abundances

The anorthositic nature of the Y-86032 meteorite is manifested by the REE pattern, in particular by the Sm/Eu ratio, the high value for Ca and the rather low concentration of Fe (Tables 4a and b). Material of this composition is found in the lunar highlands. For comparison with the data of Y-86032, Table 4a also gives the concentrations of the major and minor elements of Y-82193 and the range of values reported for Y-82192. The elemental concentrations in Y-86032 lie in the range found for the paired meteorites Y-82192/3 for most elements. The concentrations of the trace elements Co, Ba, La, Sm, Eu, Hf, Th, and U (Table 4b) also match the range found for Y-82192/3. Since only few data have been reported so far for Y-86032, the variability of its composition is not known; thus, the higher concentration of Al and the lower ones of Ti, S, Sr, and Zr in Y-86032 compared to Y-82192/3 do not disprove a possible pairing of Y-86032 with Y-82192/3. Furthermore, lunar regolith breccias, *e.g.* such as those collected at specific Apollo-16 stations show considerable compositional heterogeneities (McKay *et al.*, 1986) indicating that rocks of variable chemical composition may originate from the same source region. On the other hand, Koeberl (1988c) concludes based on the relatively low abundances of Sc, Cr, Mn, Fe, and Co and on the different siderophile element pattern of Y-86032 compared to Y-82192/3 that these meteorites originate from different impact sites.

4. History of Y-86032 and Pairing with Y-82192 and Y-82193

The history of Y-86032 can be summarized as follows: the rock formation age as deduced from the ^{40}Ar gas retention age is 3600–3900 Ma. This age and the

oxygen isotopic composition are typical for lunar highland material. The structural elements which form the Y-86032 breccia material were only briefly and, presumably only partly exposed to the solar wind when they resided on the lunar surface. Perhaps a fraction of the solar wind trapped noble gases was lost as a result of shock and/or heating events. The total exposure time to cosmic rays lasted 10.6 ± 0.6 Ma assuming 4π-exposure in free space after Y-86032 was ejected from the moon. This rock fell on Earth 72000 ± 30000 years ago.

Gas retention age, abundances of the trapped noble gases, cosmic-ray exposure age, terrestrial age and area of recovery are the same as those of Y-82192 and Y-82193 (Table 9). From these results there is no doubt that Y-86032 is paired with Y-82192/3. The fact that the chemical composition of Y-86032 and Y-82192/3 do not completely match is probably due to the heterogeneity of the source material.

Since the meteoroid producing Y-82192, Y-82193, and Y-86032 was exposed mostly to cosmic rays in free space and only briefly on the lunar surface, the total cosmic-ray exposure age of 10–11 Ma corresponds to its Moon-Earth transfer time.

Acknowledgments

Allocation of the valuable samples by the National Institute of Polar Research in Tokyo is greatly acknowledged. We thank H. TAKEDA for his efforts as consortium leader and Ch. KOEBERL for sending his preprints. We appreciate the help at various stages of this investigation by O. BRAUN, P. GUGGISBERG, Th. MICHEL, I. PETER, A. SCHALLER, and M. ZUBER. This work was supported by the Swiss National Science Foundation, and by the U.S. National Science Foundation grant EAR 8616255.

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(Received September 29, 1988; Revised manuscript received December 28, 1988)