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Noble gas and chronological study of Asuka eucrites: A-880761 and A-881388 are paired, but A-880702 is not

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Abstract: Noble gas isotopic and elemental compositions of three Antarctic eucrites Asuka-880702, Asuka-880761 and Asuka-881388 have been measured by two steps of heating temperatures (400 and 1750℃). Cosmic-ray exposure ages calculated from cosmogenic ^{21}Ne were 20.5, 32.3 and 29.7 m.y. for A-880702, A-880761 and A-881388, respectively. Combining the exposure ages with ^{81}Kr-Kr apparent exposure ages, terrestrial ages of 0.20, 0.22 and 0.23 m.y. were derived for A-880702, A-880761 and A-881388, respectively. ^{244}Pu-Xe ages based on fissiogenic Xe isotopes showed that the Asuka eucrites began Xe retention at around the crystallization age of Angra dos Reis. Among the Asuka eucrites, A-880702 is about 20 m.y. older than the others. From the noble gas and age data described above, we conclude that A-880761 and A-881388 are paired, but A-880702 is not.

key words: eucrite, noble gases, pairing, cosmic-ray exposure ages, ^{244}Pu-Xe ages

1. Introduction

Asuka-880702 (A-880702), Asuka-880761 (A-880761) and Asuka-881388 (A-881388), classified as eucrites, have been studied for noble gas concentrations and isotopic compositions. These meteorites were collected by Asuka wintering party of 29th Japanese Antarctic Research Expedition (Yanai *et al*., 1993). They were recovered as small masses, weighing about 11 g for A-880702, 65 g for A-880761 and 16 g for A-881388 around the Sør Rondane Mountains in Queen Maud Land, East Antarctica (Yanai, 1989; Naraoka *et al*., 1990). The A-881388 eucrite is unbrecciated, fine-grained recrystallized eucrite (Yanai, 1993; Takeda *et al*., 1997) and experienced a strong thermal metamorphism on the asteroid 4 Vesta, before the impact event excavated the meteorite (Yamaguchi *et al*., 1997). A-880761 eucrite shows a fine-grained granulitic texture similar to A-881388 (Kojima and Imae, 2002). A-880702 also shows a granulitic texture with some parts of basaltic texture indicated by the presence of plagioclase laths. This eucrite contains minor minerals such as silica minerals, oxide minerals and troilite (Kojima and Imae, 2002). For A-881388, a ^{39}Ar-^{40}Ar age of 4.480±0.007 b.y. has been reported by Bogard and Garrison (2003).

A brief report on noble gases of the meteorites has been presented at the 28th Symposium on Antarctic meteorites held in the National Institute of Polar Research,

Tokyo (Park and Nagao, 2004). We report here the noble gas concentrations and isotopic ratios of A-880702, -880761, -881388. The cosmic-ray exposure ages were calculated for the ejection history of Asuka eucrites from the parent body; asteroid 4 Vesta (Binzel and Xu, 1993). Terrestrial ages calculated from ^{81}Kr-Kr apparent ages combined with ^{21}Ne exposure ages, and ^{244}Pu-Xe ages are also presented. Paring between A-880761 and A-881388 will be revealed from the whole data set.

2. Experimental method

Three eucrites were analyzed by using a mass spectrometric system (modified-VG 5400/MS-II) with an extraction furnace, purification system and standard gas system at the Laboratory for Earthquake Chemistry, University of Tokyo. We used considerably bigger samples than usual analysis, *i.e.*, A-880702 (0.1734 g), A-880761 (0.1719 g) and A-881388 (0.1636 g), because of the measurement of the cosmogenic radionuclide ^{81}Kr, whose concentration is as low as $\leq 3\times10^{-13}$cm^3 STP/g in eucrites (*e.g.*, Miura *et al.*, 1998). The purification line was heated at about 250°C for one night to get ultra high vacuum condition. The samples loaded in a sample holder were also heated at the temperature of 150°C to remove atmospheric noble gas contamination. A Mo-crucible in the extraction furnace was heated at about 1800°C repeatedly for degassing.

Noble gas extraction from the sample was organized at two temperature steps of 400°C and 1750°C, separately, in order to extract adsorbed terrestrial gases at the low temperature step. At the higher temperature of 1750°C, the sample was totally melted for the ^{81}Kr measurement. The gases were purified by using two Ti-Zr getters heated at about 800°C. The purified noble gases were separated into four fractions (He-Ne, Ar, Kr, and Xe), and then measured separately; He and Ar were measured by using a Daly-multiplier system, and Ne, Kr and Xe by an ion-counting system.

Blank levels for 1750°C were 1.5×10^{-10}, 3.8×10^{-12}, 7.0×10^{-9}, 2.2×10^{-13} and 2.6×10^{-14} cm^3 STP for ^{4}He, ^{20}Ne, ^{40}Ar, ^{84}Kr and ^{132}Xe, respectively. The blank levels for ^{4}He, ^{20}Ne, ^{40}Ar and ^{132}Xe were negligibly small, *i.e.*, less than 1% of the amount of noble gases released from the eucrite samples, while the ^{84}Kr blank level was about 2%. Blank corrections were applied for all noble gas data.

3. Results and discussion

Noble gas concentrations and isotopic ratios of A-880702, A-880761, and A-881388 are presented in Table 1. Uncertainties of the concentrations are estimated as about 5% for He and Ne and about 10% for the Ar, Kr, and Xe, and the experimental errors for the isotopic ratios in the table are 1σ. Released amounts of noble gases at the low temperature step (400°C) are much smaller than those at the temperature of 1750°C. One exception is the case of He for A-880761, where almost half of the total He was released at the 400°C step. In this case, the sample was dropped into the crucible which was still hotter than 400°C because of an insufficient cooling time after pre-degassing of the crucible. In the following discussion, we will use noble gas data from 1750°C extraction step except for He from A-880761. Judging from the release patterns of He for A-880702 and A-881388, ^{3}He/^{4}He ratios of the low temperature

Table 1. Isotopic ratios and concentrations of He, Ne, Ar, Kr and Xe in Asuka eucrites.

Meteorite	Temp. (℃)	^{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
A-880702	400	19	0.00112 ±0.00005	0.049	1.081 ±0.038	0.703 ±0.017	0.017	0.1945 ±0.0041	293.6 ± 2.1
	1750	65200	0.00338 ±0.00004	36.8	0.8363 ±0.0020	0.7922 ±0.0015	8.87	1.225 ±0.017	1386.5 ± 22.5
A-880761	400	24200	n.d. ±	0.27	0.874 ±0.019	0.815 ±0.011	0.80	1.306 ±0.011	852.4 ± 8.0
	1750	30300	0.00729 ±0.00021	63.6	0.8288 ±0.0032	0.8607 ±0.0018	24.7	1.4478 ±0.0081	549.9 ± 2.8
A-881388	400	34	0.00282 ±0.00011	0.022	1.295 ±0.036	0.693 ±0.033	0.018	0.312 ±0.009	340.6 ± 2.2
	1750	54100	0.00738 ±0.00024	60.0	0.8373 ±0.0017	0.8752 ±0.0019	33.8	1.4659 ±0.0057	536.1 ± 2.1

He, Ne, and Ar concentration in 10^{-9} cm^3 STP/g.
n.d.＝not determined.

Asuka	Temp. (℃)	^{84}Kr	^{78}Kr/^{84}Kr	^{80}Kr/^{84}Kr	^{81}Kr/^{84}Kr	^{82}Kr/^{84}Kr	^{83}Kr/^{84}Kr	^{86}Kr/^{84}Kr
880702	400	0.63	0.0089 ±0.0013	0.0402 ±0.0051	n.m. ±	0.1920 ±0.0125	0.1910 ±0.0092	0.3075 ±0.0176
	1750	74.9	0.0510 ±0.0005	0.1483 ±0.0011	0.00115 ±0.00016	0.3389 ±0.0029	0.3782 ±0.0028	0.2868 ±0.0017
880761	400	9.18	0.0070 ±0.0004	0.0415 ±0.0011	n.m. ±	0.2038 ±0.0019	0.2022 ±0.0034	0.3029 ±0.0057
	1750	51.1	0.1791 ±0.0020	0.5090 ±0.0056	0.00308 ±0.00038	0.8406 ±0.0113	1.0760 ±0.0132	0.1707 ±0.0035
881388	400	0.96	0.0074 ±0.0016	0.0443 ±0.0035	n.m. ±	0.2083 ±0.0094	0.2125 ±0.0131	0.3120 ±0.0139
	1750	55.1	0.1906 ±0.0025	0.5558 ±0.0068	0.00359 ±0.00040	0.9157 ±0.0086	1.1663 ±0.0135	0.1508 ±0.0032

Kr concentration in 10^{-12} cm^3 STP/g.
n.m.＝not measured.

Asuka	Temp.(℃)	^{132}Xe	^{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
880702	400	0.09	0.0219 ±0.0049	0.0055 ±0.0029	0.0764 ±0.0062	1.157 ±0.051	0.160 ±0.022	0.858 ±0.064	0.371 ±0.029	0.323 ±0.033
	1750	23.60	0.0322 ±0.0005	0.0485 ±0.0007	0.1156 ±0.0009	0.801 ±0.008	0.1518 ±0.0015	0.7348 ±0.0053	0.5125 ±0.0069	0.5047 ±0.0048
880761	400	5.49	0.0046 ±0.0005	0.0039 ±0.0006	0.0723 ±0.0019	1.008 ±0.017	0.152 ±0.003	0.790 ±0.017	0.388 ±0.007	0.333 ±0.008
	1750	25.9	0.0411 ±0.0012	0.0733 ±0.0004	0.1546 ±0.0019	1.012 ±0.008	0.1864 ±0.0020	0.8616 ±0.0065	0.4864 ±0.0050	0.4535 ±0.0049
881388	400	0.68	0.0084 ±0.0011	0.0055 ±0.0016	0.0763 ±0.0056	0.988 ±0.042	0.146 ±0.011	0.794 ±0.018	0.379 ±0.013	0.321 ±0.014
	1750	28.3	0.0448 ±0.0009	0.0756 ±0.0014	0.1635 ±0.0010	0.971 ±0.010	0.1889 ±0.0015	0.8842 ±0.0065	0.4911 ±0.0051	0.4728 ±0.0030

Xe concentration in 10^{-12} cm^3 STP/g.

fractions do not affect $^{3}He/^{4}He$ values of their total He. Hence, in the following discussion we assume that the $^{3}He/^{4}He$ ratio of the low temperature fraction from A-880761 is the same as that for 1750°C and the He concentration of this meteorite is the sum of the two temperature fractions.

Table 1 shows some similarities in noble gas concentrations and isotopic ratios between A-880761 and A-881388. On the other hand, the concentrations of ^{22}Ne and ^{36}Ar in A-880761 and A-881388 are twice and three times more than those in A-880702. The observed $^{20}Ne/^{22}Ne$, $^{21}Ne/^{22}Ne$ and $^{38}Ar/^{36}Ar$ ratios indicate that Ne is almost entirely cosmogenic, whereas Ar contains a small contribution of trapped Ar probably from atmospheric contamination. The isotopic ratio of $^{40}Ar/^{36}Ar$ in A-880702 is much higher than the other two eucrites ($^{40}Ar/^{36}Ar = 1386.5 \pm 22.5$ for A-880702, 549.9 ± 2.8 for A-880761, 536.1 ± 2.1 for A-881388). The higher $^{40}Ar/^{36}Ar$ ratio for A-880702 than those for others is mainly due to the lower concentrations of ^{36}Ar in this eucrites as noted above. The data suggest the paring of A-880761 and A-881388, although these three Asuka eucrites were discovered at the same location (Kojima and Imae, 2002).

Because the noble gases are generally composed of trapped, radiogenic, cosmogenic and fissiogenic components, we will show how each noble gas component can be interpreted.

3.1. Cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar and cosmic-ray exposure ages

The concentrations of the cosmogenic nuclides ^{3}He, ^{21}Ne, and ^{38}Ar ($10^{-9}cm^{3}$ STP/g) are (1) A-880702: 221, 29.0, 10.5, (2) A-880761: 390, 54.8, 36.4, (3) A-881388: 392, 52.5, 49.2, respectively (Table 2). The cosmic-ray exposure ages T_3, T_{21} and T_{38} are calculated from the concentrations of ^{3}He, ^{21}Ne and ^{38}Ar. Their production rates were calculated with the formulae for eucrites proposed by Eugster and Michel (1995) and the chemical compositions for A-881388 (Yanai, 1993). The exposure ages (m.y.) are 13.2 (T_3), 20.5 (T_{21}) 6.6 (T_{38}) for A-880702, 23.8 (T_3), 32.3 (T_{21}), 22.7 (T_{38}) for A-880761 and 23.8 (T_3), 29.7 (T_{21}), 30.7 (T_{38}) for A-881388. The short ^{3}He ages (T_3) compared with the ^{21}Ne ages (T_{21}) may have resulted from the diffusion loss of ^{3}He. Because the He mass is lighter than the other noble gases, it is lost at lower temperatures (*e.g.*, Heymann *et al.*, 1968; Shukolyukov and Begemann, 1996a). The ^{38}Ar age agrees with the ^{21}Ne age for A-881388, where the ages were calculated based on the chemical compositions reported for this meteorite (Yanai, 1993). On the other hand, two eucrites A-880702 and A-880761 show short ^{38}Ar ages (T_{38}) compared with the ^{21}Ne ages, for which chemical compositions were assumed to be similar to those of A-881388. Hence, the discordant and short T_{38} exposure ages for A-880702 and A-880761 might result from chemical heterogeneity of these Asuka meteorites. This may be supported

Table 2. Concentrations of cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar, and cosmic-ray exposure ages.

Meteorite	^{3}He	^{21}Ne	^{38}Ar	P_3	P_{21}	P_{38}	T_3	T_{21}	T_{38}
	10^{-9} cm^3 STP/g			10^{-9} cm^3 STP/g/m.y.			m.y.		
A-880702	211	29.0	10.5	15.9	1.42	1.60	13.2	20.5	6.6
A-880761	390	54.8	36.4	16.4	1.70	1.60	23.8	32.3	22.7
A-881388	392	52.5	49.2	16.5	1.76	1.60	23.8	29.7	30.7

by the positive correlation between the T_{38}/T_{21} ratios and ^{40}Ar concentrations for these eucrites, *i.e.*, A-880702 with the lowest T_{38}/T_{21} (0.32) has the lowest ^{40}Ar concentration (1.2×10^{-5}cm^3 STP/g) and A-880761 has intermediate values between those for A-880702 and A-881388. This may suggest low concentrations of target elements for ^{38}Ar production such as K and Ca in A-880702 eucrite. Accordingly, the large discrepancy between the ^{21}Ne and ^{38}Ar ages for A-880702 could be due to higher Mg and lower Ca concentrations than the other two eucrites.

Otherwise, it is possible that ^{38}Ar was lost during weathering as pointed out for E-chondrites by Okazaki *et al*. (2000) and Patzer and Schultz (2001). Increase in terrestrial heavy noble gases with enhanced concentration of Kr is also observed for ordinary chondrites from hot deserts and Antarctica, which can be attributed to a terrestrial weathering (Scherer *et al*., 1994). The ^{84}Kr concentration for A-880702 is about 50% higher than those for other two eucrites, while the ^{132}Xe concentrations are almost identical among them (Table 1). Though this might be a result of terrestrial weathering of this eucrite, the Kr concentration is much lower than the observed values for ordinary chondrites reported by Scherer *et al*. (1994). The relatively small contribution of terrestrial noble gases in the eucrites studied in this work would indicate that weathering effects on these eucrites are minor and the low concentrations of cosmogenic ^{38}Ar in A-880702 and A-880761 are due to low concentrations of target elements, such as K and Ca in these eucrites.

As will be shown, the residence time of the Asuka eucrites on the Earth was as long as 0.20–0.23 m.y. Since Mg bearing silicate minerals which contain cosmogenic Ne are relatively resistant to weathering, we adopt T_{21} as the exposure age of Asuka eucrites in the following discussion. A-880761 and A-881388 show similar cosmic-ray exposure ages about 30 m.y., while that of A-880702 is about 20 m.y. This suggests that the two eucrites A-880761 and A-881388 would have experienced the same ejection event and might be one single body before falling onto Antarctica.

Eugster and Michel (1995) pointed out that the exposure ages reported so far for eucrites produce 5 age clusters from 6 to 73 m.y. which may represent multiple ejection events for HED meteorites from their parent bodies, and that the parent bodies may be multiple 4 Vesta-derived objects at the 3 : 1 resonance region. Shukolyukov and Begemann (1996a) applied ^{81}Kr-Kr method to eucrite falls and also found 5 clusters of exposure ages at about 7, 10, 14, 22 and 37 m.y. The exposure age for A-880702 belongs to the cluster at 22 ± 2 m.y. formed by Millbillillie, Pomozdino, Sioux County and Vetluga. Though the age of 30 m.y. does not belong to any other clusters, some eucrites such as Chervony, Jonsac, Lakengaon and Medanitos (see Table A9 in Eugster and Michel, 1995) have ages around 30 m.y.

3.2. Cosmogenic Kr isotopes and ^{81}Kr terrestrial ages

Cosmogenic ^{81}Kr generally shows high concentration in eucrites compared with other types of meteorites because they are enriched in target elements such as Sr, Y and Zr. The ^{81}Kr and other cosmogenic Kr isotopes give information about the irradiation condition to cosmic-rays in space. Figure 1 and Table 3 show the cosmogenic Kr isotopic ratios calculated by subtracting trapped Kr isotopes. In this calculation, we assumed terrestrial Kr isotopic composition and cosmogenic ^{86}Kr/^{83}Kr ratio of 0.015

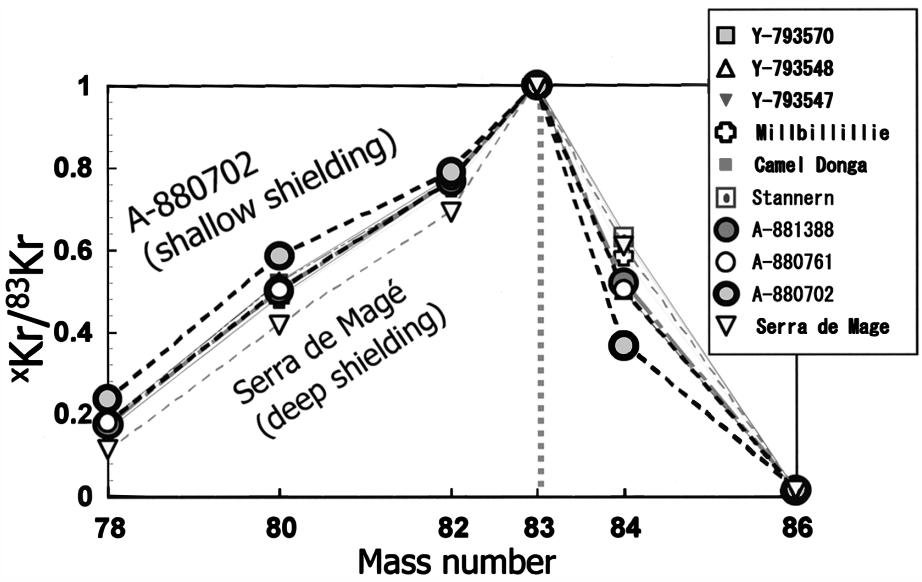

Fig. 1. Cosmogenic Kr isotopic ratios normalized on ^{83}Kr. Trapped Kr was subtracted from the measured ratios assuming $(^{86}Kr/^{83}Kr)_{cos}=0.015$.
Data source: Y-793570, Y-793548, Y-793547 and Millbillillie (Miura, 1995); Camel Donga and Stannern (Eugster and Michel, 1995); Serra de Magé (Shukolyukov and Begemann (1996a).

Table 3. Cosmogenic Kr isotopic ratios.

	^{78}Kr	±	^{80}Kr	±	^{81}Kr	±	^{82}Kr	±	^{83}Kr	^{84}Kr	±	reference
A-880702	0.238	0.038	0.584	0.114	0.00602	0.00119	0.790	0.288	=1	0.37	1.01	this work#
A-880761	0.181	0.026	0.502	0.075	0.00316	0.00060	0.758	0.124	=1	0.50	0.18	this work#
A-881388	0.174	0.025	0.500	0.074	0.00333	0.00060	0.767	0.121	=1	0.52	0.14	this work#
Stannern	0.179		0.495		—		0.765		=1	0.63		1)
Camel Donga	0.162		0.487		—		0.76		=1	0.64		2)
Millbillillie 1	0.154		0.48		—		0.75		=1	0.6		2)
Millbillillie 2	0.166		0.482		—		0.752		=1	0.583		3)
Y-75011	0.182		0.512		—		0.765		=1	0.607		4)
Y-793547	0.184		0.520		0.00262		0.766		=1	0.494		3)
Y-793548	0.183		0.524		0.00258		0.779		=1	0.499		3)
Y-793570	0.182		0.520		0.00313		0.767		=1	0.498		3)

#Calculated assuming $(^{86}Kr/^{83}Kr)_{cos}=0.015$.
References: 1) Marti (1967), 2) Eugster and Michel (1995), 3) Miura (1995), 4) Miura *et al.* (1993).

(Marti and Lugmair, 1971). The ratios for A-880702, A-880761, A-881388 and the some eucrites, which have been reported previously (Miura, 1995; Eugster and Michel, 1995; Shukolyukov and Begmann, 1996a) indicate variable shielding effects. A-880702 seems to have been irradiated at shallow shielding, while Serra de Magé shows very deep shielding. The yielding curves of A-880761 and A-881388 show the same shapes, and are similar to those of other eucrites listed in the Table 3. The two Asuka eucrites

should have experienced the same radiation hardness at the same shielding depth.

Figure 2 explains the correlations of cosmogenic $^{22}Ne/^{21}Ne$ and cosmogenic $^{78}Kr/^{83}Kr$, in which A-880702, A-880761 and A-881388 as well as reported some eucrites (Miura *et al*., 1998) were plotted. The eucrite correlation line is given by Eugster and Michel (1995). Because the production of ^{21}Ne and ^{78}Kr are more sensitive to shielding conditions than ^{22}Ne and ^{83}Kr, the plot of cosmogenic $^{22}Ne/^{21}Ne$ and cosmogenic $^{78}Kr/^{83}Kr$ is a useful indicator for shielding condition. Three Asuka eucrites are located at slightly higher Kr ratios on the eucrite correlation line. Most eucrites, *e.g*., Camel Donga, Millbillillie, Juvinas, and other Antarctic eucrites (Miura *et al*., 1998) plot along the eucrite correlation line given by Eugster and Michel (1995). The low $^{22}Ne/^{21}Ne$ and $^{78}Kr/^{83}Kr$ ratios for A-880761 and A-881388 might have resulted in larger pre-atmospheric body than that for A-880702.

Cosmogenic ^{81}Kr is used for the most reliable cosmic-ray exposure ages of meteorites, because only the isotopic ratios of cosmogenic Kr, which can be measured more precisely than the absolute abundances, are used for the calculation. Moreover, the ^{81}Kr-Kr method diminishes the uncertainties of shielding effects and target element-chemistry (Marti, 1967; Eugster *et al*., 1967). Even though the ^{81}Kr exposure age method is difficult to apply for most chondrites because of their very low concentrations of cosmogenic ^{81}Kr (in the range of 10^{-14} cm^3 STP/g) and abundant trapped Kr, this method is useful for the specific types of meteorites such as eucrite (Nagao and Ogata, 1989). If the ^{81}Kr-Kr method is applied to meteorites of long terrestrial age, the

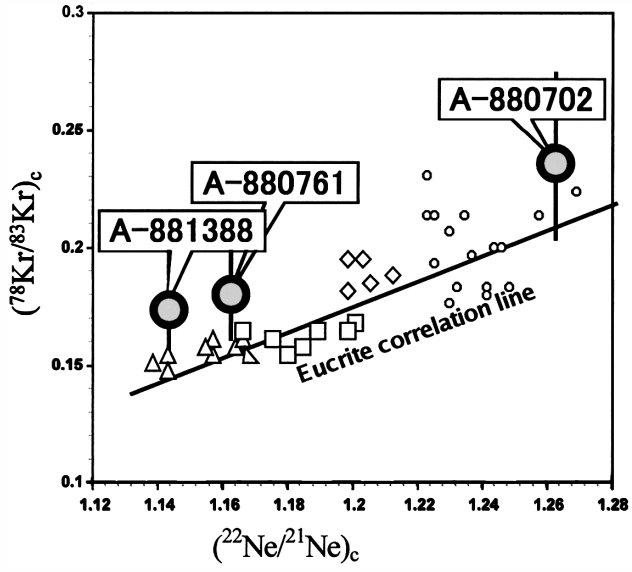

Fig. 2. Plot of cosmogenic $^{78}Kr/^{83}Kr$ versus $^{22}Ne/^{21}Ne$ for A-880702, A-880761 and A-881388. Eucrite correlation line, $(^{78}Kr/^{83}Kr)_c=0.50\ (^{22}Ne/^{21}Ne)_c-0.42$, is given by Eugster and Michel (1995).
△ Camel Donga, □ Millbillillie, ◇ Juvinas, ○ Antarctic eucrites. (Miura et al., 1998).

Table 4. Apparent exposure and terrestrial ages.

Meteorite	$T_{81\,(appa)}$	±	T_t	±
	m.y.			
A-880702	37.3	7.4	0.198	0.082
A-880761	63.6	12.0	0.224	0.080
A-881388	59.5	10.7	0.230	0.077

The apparent exposure ages, $T_{81\,(appa)}$ were calculated by ^{81}Kr-Kr method (see text), and the terrestrial ages were by the formula, $T_t = (1/\lambda)\ln(T_{81}/T_{21})$, where λ ($=3.03\times10^{-6}$ y^{-1}) is decay constant of ^{81}Kr, a half life of ^{81}Kr$=0.229\times10^6$ y. (Baglin, 1993).

obtained age becomes longer than the real exposure age due to radioactive decay of ^{81}Kr in the meteorite during its residence time on Earth. However, the "apparent exposure age" can give terrestrial age by combining with the "real exposure age" (Schultz, 1986; Freundel *et al*., 1986). The apparent ages $T_{81\,(appa)}$ (m.y.) for A-880702, A-880761 and A-881388 are 37.3±7.4, 63.6±12.0 and 59.5±10.7, respectively (Table 4). The formula from Eugster *et al*. (1967) and Marti (1967) was used for the $T_{81\,(appa)}$ calculations. Production rate ratios P_{81}/P_{83} used in the calculation were based on the cosmogenic ^{80}Kr/^{83}Kr and ^{82}Kr/^{83}Kr ratios, but the ratios based on cosmogenic ^{78}Kr/^{83}Kr (*e.g*., Marti and Lugmair, 1971) are identical with the former ones within error limits. This indicates no effect of neutron capture by ^{79}Br and ^{81}Br on the cosmogenic Kr isotopic compositions in the meteorite samples. The ^{81}Kr-terrestrial ages T_t (m.y.) were calculated as 0.198±0.082, 0.224±0.080 and 0.230±0.077 for A-880702, A-880761 and A-881388, respectively, by the equation (see caption of Table 4) from Freundel *et al*. (1986). The terrestrial ages of the Asuka eucrites (range around 0.20~0.23 m.y.) are in the range (0~0.35 m.y.) reported for Antarctic eucrites (*e.g*., Schultz, 1986; Nagao and Ogata, 1989; Miura *et al*., 1993). The obtained ages for two A-880761 and A-881388 eucrites are in good agreement within experimental errors, suggesting that they are paired.

3.3. Fissiogenic Xe isotopes and ^{244}Pu-Xe ages

Isotopic ratios corrected for cosmogenic component are presented in Table 5, where cosmogenic isotopes were subtracted by assuming that measured ^{126}Xe and ^{130}Xe are mixtures of cosmogenic and trapped components; $(^{126}\mathrm{Xe}/^{130}\mathrm{Xe})_c = 1$ (*e.g*., Miura *et al*., 1998) and $(^{126}\mathrm{Xe}/^{130}\mathrm{Xe})_t = 0.0218$ (atmospheric Xe; Ozima and Podosek, 2002). Cosmogenic ^{130}Xe amounts 30–40% of the total ^{130}Xe. Plot of ^{134}Xe/^{130}Xe *versus* ^{136}Xe/^{130}Xe in Fig. 3 clearly demonstrates the presence of ^{244}Pu-derived fission Xe for the

Table 5. Heavy Xe isotopic composition corrected for cosmogenic Xe (^{130}Xe=1).

Meteorite	^{130}Xe	^{131}Xe	±	^{132}Xe	±	^{134}Xe	±	^{136}Xe	±
A-880702	1	5.42	0.06	9.11	0.11	4.86	0.07	4.62	0.10
A-880761	1	5.02	0.07	8.02	0.10	4.13	0.03	3.85	0.03
A-881388	1	5.16	0.06	8.07	0.08	4.22	0.05	3.96	0.05

Asuka eucrites. Three Asuka eucrites are exactly plotted on the mixing line between ^{244}Pu-derived fission Xe and the terrestrial atmospheric Xe or trapped meteoritic Xe (*e.g.*, Q-Xe) with the typical eucrites (*e.g.*, Millbillillie and Camel Donga, *etc.*; Miura *et al*., 1998). Contribution from ^{238}U-fission is negligibly small as will be shown later; ^{136}Xe (U-fiss)/^{136}Xe (total excess) $<$ 10%. It is distinctive that A-880761 and A-881388 plot almost at the same position, while A-880702 shows more excess of ^{244}Pu contribution.

^{244}Pu-Xe ages for A-880702, A-880761 and A-881388, relative to the Angra dos Reis (ADOR) were calculated by using the method of Shukolyukov and Begemann (1996b) (Table 6). The followings are the modified formulae in Miura *et al*. (1998) :

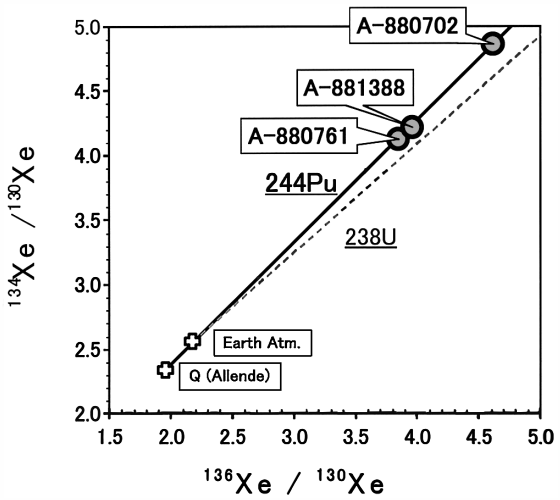

Fig. 3. Plot of ^{134}Xe/^{130}Xe vs. ^{136}Xe/^{130}Xe. The isotopic ratios have been corrected for cosmogenic Xe. Three Asuka eucrites are plotted on the mixing line between trapped (Earth atmosphere) and ^{244}Pu-fission Xe.
The errors of ^{134}Xe/^{130}Xe and ^{136}Xe/^{130}Xe are within the symbols of Asuka eucrites (see Table 5).
Data source: Earth Atmosphere (Ozima and Podosek, 2002); Q-Allende (Wieler et al., 1992).

Table 6. Concentrations of cosmogenic ^{126}Xe, ^{244}Pu-derived ^{136}Xe, and ^{244}Pu-Xe ages for Asuka eucrites.

Meteorite	$[^{126}Xe]_c$	$[^{136}Xe]_{excess}$	$[^{136}Xe]_{Pu}$	^{244}Pu	$\Delta T_{A\text{-}ADOR}$	±	T_{136}	±
	10^{-12} cm^3 STP/g			ppb	m.y.		b.y.	
A-880702	1.11	6.10	5.75	0.90	7	15	4.565	0.015
A-880761	1.81	5.12	4.77	0.74	−20	15	4.538	0.015
A-881388	2.09	5.90	5.55	0.86	−28	32	4.530	0.032

Concentration of ^{136}Xe from ^{238}U-fission was calculated as 0.35×10^{-12} cm^3 STP/g assuming 100 ppbU and 4.5 b.y. retention age. Concentrations of ^{136}Xe from ^{244}Pu-fission were obtained by subtracting the ^{238}U-fission Xe from the $^{136}Xe_{excess}$. Concentrations of ^{244}Pu at the onset of Xe retention were calculated based on the branching ratio of 1.25×10^{-3} and ^{136}Xe fission yield of 5.6% (Ozima and Podosek, 2002).

$$\Delta T_{\text{A-ADOR}} = \frac{1}{\lambda_{244}} \ln \frac{\left(\frac{[^{136}\text{Xe}]_{\text{Pu}}}{[^{126}\text{Xe}]_{\text{LREE}}}\right)_{\text{A}}}{\left(\frac{[^{136}\text{Xe}]_{\text{Pu}}}{[^{126}\text{Xe}]_{\text{LREE}}}\right)_{\text{ADOR}}}, \quad (1)$$

and

$$[^{126}\text{Xe}]_{\text{LREE}} = \frac{[^{126}\text{Xe}]_{\text{c}}}{T_{\text{exp}}} \cdot \frac{1}{1 + \frac{P_{\text{Ba}}}{P_{\text{LREE}}} \frac{[\text{Ba}]}{[\text{LREE}]}}. \quad (2)$$

In the formulae λ_{244} ($=8.47\times10^{-9}$ y^{-1}) is the decay constant of ^{244}Pu, $[^{136}\text{Xe}]_{\text{Pu}}$ concentration of ^{136}Xe derived from ^{244}Pu-fission, $[^{126}\text{Xe}]_{\text{LREE}}$ spallogenic ^{126}Xe from light REE (La+Ce+Nd), $[^{126}\text{Xe}]_{\text{c}}$ measured concentration of cosmogenic ^{126}Xe produced from Ba and LREE, T_{exp} exposure age, $P_{\text{Ba}}/P_{\text{LREE}}$ production rate ratio for cosmogenic ^{126}Xe from Ba to LREE, and [Ba] and [LREE] are the concentrations of Ba and LREE, respectively. Though U concentrations for the Asuka eucrites studied in this work are not yet available at present, the concentrations reported for noncumulate eucrites are in the range from 88 ppb (Ibitira) to 190 ppb (Pomozdino) with average of 125±35 ppb for 15 eucrites, while the concentrations for cumulate eucrites (27 and 13 ppb for Moore County and Serra de Magé, respectively) are much lower than those for noncumulate ones (Kitts and Lodders, 1988). The ^{238}U-fission ^{136}Xe was calculated with the U contents of 100 ppb and 4.5 b.y. as a retention age. The assumed retention age of 4.5 b.y. would be valid because of the presence of fissiogenic Xe from the short lived ^{244}Pu in these eucrites. Branching ratio and production yield for ^{136}Xe from ^{238}U-decay are 5.45×10^{-7} and 6.3%, respectively (Ozima and Podosek, 2002). Concentration of ^{136}Xe from ^{244}Pu-fission was calculated from the excess ^{136}Xe by subtracting ^{136}Xe from ^{238}U-fission, which amounts 6–7% of the total concentration of excess ^{136}Xe. Concentrations of ^{244}Pu at the onset of Xe retention were calculated based on the branching ratio of 1.25×10^{-3} and ^{136}Xe fission yield of 5.6% (Ozima and Podosek, 2002). Obtained ^{244}Pu concentrations of 0.74–0.90 ppb are in the reported range for eucrites (Miura *et al*., 1998).

For the $P_{\text{Ba}}/P_{\text{LREE}}$ ratio, 1.82±0.33 (Hohenberg *et al*., 1981; Shukolyukov and Begemann, 1996b; Miura *et al*., 1998) was adopted. Because chemical compositions including REE have not been reported for the Asuka eucrites, we used the [Ba]/[LREE] ratio of 2 (*e.g*., Shukolyukov and Begemann, 1996b; Miura *et al*., 1998). For the cosmic-ray exposure age T_{exp}, the values T_{21} in Table 2 were used in the calculation. Concentrations of cosmogenic ^{126}Xe, fissiogenic ^{136}Xe from ^{244}Pu and ^{238}U are given in Table 6. Though there seem to be large ambiguities in the adopted values, calculated ^{244}Pu-Xe ages relative to that of Angra dos Reis (ADOR) became as 7±15, −20±15 and −28±32 m.y. for A-880702, A-880761 and A-881388, respectively (negative age means later onset for Xe retention relative to ADOR). The ages belong to the Pasamonte-Juvinas group with old ages close to that of ADOR (Shukolyukov and Begemann, 1996b). The absolute ^{244}Pu-Xe ages in Table 6 are calculated based on the reported Pb-Pb age of 4.5578 b.y. for ADOR (Lugmair and Galer, 1992). The ages of A-880702, A-880761 and A-881388 are 4.565±0.015, 4.538±0.015 and 4.530±0.032 b.y., respectively. The absolute age of A-881388 is older than the ^{39}Ar-^{40}Ar age of

4.480±0.007 b.y. (Bogard and Garrison, 2003), probably due to higher retentivity of Xe compared with Ar.

On the basis of noble gas data and ages data presented above, A-880761 and A-881388 are paired, but A-880702 is not. This is supported by the textural similarity between A-880761 and A-881388 reported in Kojima and Imae (2002).

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