Geochemical Journal, Vol. 47, pp. 83 to 88, 2013

NOTE

Simple relationship between ^{26}Al production rate and major elemental composition of meteorite samples

H. KUSUNO,[1]* T. FUKUOKA[1] and H. MATSUZAKI[2]

[1]Graduate School of Geo-environmental Science, Rissho University,
1700, Magechi, Kumagaya, Saitama 360-0194, Japan
[2]School of Engineering, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

(*Received August 27, 2012; Accepted December 5, 2012*)

Estimation of ^{26}Al (half-life = 705 kyr) content at the time of meteorite fall is required to calculate the terrestrial age of meteorites using the ^{26}Al content. Previous studies (e.g., Cressy, 1971; Hampel *et al.*, 1980) provided empirical equations for the estimation of ^{26}Al content in meteorites at the time of meteorite fall. However, the equations overestimate the ^{26}Al content of howardites and eucrites, which have a high Al content (5–8%). In this study, we present a new simple empirical equation based on the relationship between ^{26}Al content and the content of two main target elements, Al and Si, in 37 falls meteorites from various classes (one howardite, 10 eucrites, 13 diogenites, 8 chondrites, 3 ureilites, and one angrite). The equation estimates the ^{26}Al content of howardites and eucrites at the time of meteorite fall within a 9% difference of the measured ^{26}Al content. This difference is lower than in any other equations presented in previous literature.

Keywords: production rate, ^{26}Al, terrestrial age, howardite, eucrite

INTRODUCTION

Cosmogenic ^{26}Al (half-life = 705 kyr) is a useful tool for dating the terrestrial age of meteorites. ^{26}Al in meteorites is produced by a nuclear reaction via cosmic-ray irradiation. If the irradiation time is more than 10 times as long as the half-life, the ^{26}Al activity reaches saturation. After a meteorite falls to Earth, the ^{26}Al content decreases according to the decay constant. The production of ^{26}Al and other cosmogenic nuclides are mainly dependent on several factors: the target element compositions, the primary cosmic-ray flux, and the pre-atmospheric sizes and shape of the meteorites. To calculate the ^{26}Al production rate of a meteorite, numerical simulations using Monte Carlo particle production have been presented (e.g., Masarik and Reedy, 1994; Herpers *et al.*, 1995; Leya *et al.*, 2000; Leya and Masarik, 2009). However, these simulations use empirical production rates because the cross section of ^{26}Al production by high energy neutron reactions is not known.

Cressy (1971) and Hampel *et al.* (1980) presented empirical equations, which calculated the ^{26}Al content in meteorites at the time of the meteorite's fall (P_{26}), based on the relationship between ^{26}Al content and the elemental composition of bulk or minerals in falls chondrites. However, the P_{26} of howardites and eucrites calculated in equations by Cressy and Hampel, are overestimated. Aylmer *et al.* (1988) presented the empirical ^{26}Al production rate of eucrites. However, the P_{26} of howardites and eucrites calculated by Aylmer's production rate tends to be higher than the actual ^{26}Al contents.

In this study, we propose a new empirical equation for the ^{26}Al production rate based on the relationship between the bulk ^{26}Al content and the content of major elements in various classes of 37 falls stony meteorites (one howardite, 10 eucrites, 13 diogenites, 8 chondrites, 3 ureilites, and one angrite). 18 of the 37 meteorites were measured in this study and data of another 19 meteorites were obtained from literature. The relationship between ^{26}Al content and content of target element is obtained clearly by using various classes of meteorite with different elemental composition. Production rate of ^{26}Al in meteorites is strongly affected by the shielding effect. The shielding condition is not constant, because shielding effect depends on depth and shape of meteoroid. We expected the shielding effect to be averaged out by measuring ^{26}Al content from 37 meteorite samples.

---

*Corresponding author (e-mail: cosmo-geochem_hk@ris.ac.jp)

Table 1. The ^{26}Al content and major elemental composition of 18 falls meteorite

Meteorite name	Class	^{26}Al			Si	Ti	Al	Fe	Mn	Mg	Ca	Na	Ni	S
		dpm/kg			%									
Béréba	Eucrite	95.8	±	1.7	25.9	0.44	6.50	11.0	0.396	4.0	7.2	0.313	—	—
Bouvante	Eucrite	80.2	±	1.3	24.7	0.54	5.67	15.2	0.411	3.5	6.6	0.392	—	—
Jonzac	Eucrite	92.5	±	2.5	24.0	0.40	6.74	13.3	0.413	3.9	7.8	0.371	—	—
Juvinas	Eucrite	92.7	±	2.8	24.3	0.41	6.55	13.7	0.444	3.8	7.1	0.340	—	—
Millbillillie	Eucrite	89.7	±	0.8	23.9	0.40	6.56	15.3	0.472	3.9	6.3	0.325	—	—
Talampaya	Eucrite	88.7	±	2.2	23.6	0.07	6.54	11.1	0.398	7.9	6.4	0.177	—	—
Bilanga	Diogenite	77.8	±	1.7	24.8	0.04	0.44	12.2	0.348	18	0.5	0.009	—	—
Johnstown	Diogenite	81.7	±	2.0	24.7	0.05	0.62	13.6	0.395	16	1.3	0.005	—	—
Shalka	Diogenite	70.2	±	1.4	25.7	0.06	0.38	12.3	0.438	16	0.6	0.016	—	—
Tatahouine	Diogenite	74.4	±	2.0	26.2	0.04	2.23	9.7	0.402	15	1.2	0.060	—	—
Allende[1]	CV3	52.5	±	0.7	15.6	0.09	2.04	24.3	0.158	13	2.1	0.421	1.34	2.2
Lance[1]	CO3.4	67.7	±	1.5	15.9	0.16	1.44	25.8	0.144	14	1.8	0.446	1.40	2.0
Ningqiang[1]	CK3	51.4	±	0.6	15.1	0.13	1.78	21.6	0.155	14	1.9	0.527	1.27	1.6
Valera[1]	L5	65.9	±	0.6	18.5	0.04	2.10	21.6	0.278	14	1.2	0.614	1.20	2.2
Mbale[1]	L5-6	71.1	±	2.0	18.5	0.07	1.35	21.6	0.304	15	1.3	0.832	1.20	2.2
Kyushu[1]	L6	67.0	±	1.9	18.5	0.10	0.91	21.6	0.205	11	1.4	0.613	1.20	2.2
Oum Dreyga[1]	H3-5	56.5	±	1.6	16.9	0.08	1.26	27.8	0.264	15	1.3	0.688	1.60	2.0
Dashoguz[1]	H5	63.9	±	0.8	16.9	0.06	1.33	27.8	0.326	17	1.6	0.785	1.60	2.0
Error %[2]		0.9–3.0			1–4[3]	4–46	0.4–2	0.1–1	0.6–1	3–5	1–10	0.8–35	—	—

"—" means no data.

[1] *Si, Fe, Ni, and S contents are from Hutchison (2004).*

[2] *Errors due to counting error.*

[3] *Errors of Si were calculated from counting errors of other elements.*

Table 2. The ^{26}Al content and major elemental composition of 19 falls meteorite (from literature)

Meteorite name	Class	^{26}Al			Si	Ti	Al	Fe	Mn	Mg	Ca	Na	Ni	S	Reference
		dpm/kg			%										
Yurtuk	Howardite	71.1	±	4.7	25.08	0.28	4.61	11.7	0.336	8.9	4.8	0.190	—	—	1, 2
Haraiya	Eucrite	85.0	±	1.3	23.42	0.32	6.62	14.6	0.332	4.2	7.3	0.312	—	—	1, 2
Moore County	Eucrite	73.9	±	3.6	22.55	0.26	6.70	13.4	0.314	5.7	6.7	—	—	—	1, 3
Nuevo Laredo	Eucrite	81.4	±	3.1	23.10	0.50	6.46	15.2	0.350	3.3	7.4	0.378	—	—	1, 4
Sioux County	Eucrite	103.5	±	3.1	22.96	0.35	6.88	14.3	0.332	4.1	7.5	0.304	—	0.07	1, 4
Stannern	Eucrite	109.8	±	3.0	23.19	0.59	6.51	13.8	0.320	4.2	7.7	0.460	—	—	1, 4
Aioun el Atrouss	Diogenite	67.7	±	1.6	23.94	0.08	0.54	12.0	0.400	15	0.9	—	—	—	5
Ellemeet	Diogenite	70.4	±	1.7	22.90	0.04	0.55	12.8	0.450	15	0.4	—	—	—	5
Garland	Diogenite	70.5	±	1.5	24.54	0.09	1.16	12.6	0.430	13	1.3	—	—	—	5
Johnstown-1	Diogenite	67.2	±	2.4	24.50	0.06	0.79	12.4	0.289	15	1.3	0.015	—	0.22	1, 4
Johnstown-2	Diogenite	75.9	±	2.3	24.74	0.07	0.51	11.7	0.390	15	0.8	—	—	—	5
Roda	Diogenite	52.5	±	1.5	23.44	0.08	0.58	13.1	0.380	16	0.8	—	—	—	5
Shalka-05*	Diogenite	63.8	±	1.8	24.64	0.05	0.39	13.0	0.440	15	0.5	—	—	—	5
Shalka-80*	Diogenite	71.3	±	1.8	24.64	0.04	0.34	12.7	0.440	15	0.5	—	—	—	5
Tatahouine	Diogenite	80.3	±	2.3	24.34	0.04	0.27	11.5	0.390	15	0.5	—	—	—	5
Dyalpur	Ureilite	55.8	±	4.8	19.55	0.11	0.17	10.3	0.247	23	1.0	0.059	0.13	—	1, 4
Haverö	Ureilite	43.0	±	3.0	18.81	0.04	0.14	11.0	0.223	24	0.1	0.030	0.12	—	1, 4
Novo-Urei	Ureilite	45.7	±	1.9	18.55	0.08	0.22	11.7	0.241	22	0.6	0.134	0.12	—	1, 3
Angra dos Reis	Angrite	105.1	±	5.1	20.39	1.23	4.95	7.3	0.060	6.5	16.4	0.022	—	—	1, 4

"—" means no data.

**Shalka-05 and -80 are taken 5 mm and 80 mm from fusion crust (Welten et al., 1997).*

References: 1, Nishiizumi (1987); 2, Fukuoka et al. (1977); 3, Dodd (1981); 4, Hutchison (2004); 5, Welten et al. (1997).

Table 3. Equations for estimation of ^{26}Al content in meteorites

Reference	The production rate equation for ^{26}Al
This study	$P_{26} = 3.7\,Al + 2.8\,Si$
Aylmer *et al.* (1988)	$P_{26} = 4.8\,Al + 2.7\,Si$
Hampel *et al.* (1980)	$P_{26} = 4.92\,Al + 2.74\,Si + 0.42\,Mg + 0.24\,Ca + 1.33\,S + 0.03\,Fe$
Leya and Masarik (2009)	$P_{26} = 5.46\,Al + 3.20\,Si + 0.037\,Fe$
Cressy (1971)	$P_{26} = 11.3\,Al + 2.4\,Si + 0.28\,Mg + 0.24\,Ca + 1.33\,S + 0.022\,(Fe + Ni)$

P_{26} is the calculated ^{26}Al content (dpm/kg) of meteorite at time of fall.
Al, Si, Mg, Ca, S, Fe, and Ni are the content of each element (%).

MEASUREMENTS FOR ^{26}Al CONTENT AND MAJOR ELEMENT COMPOSITION

About 0.1 g of meteorite sample was crushed and powdered on an agate mortar to homogenize the sample. Magnetic fractions of chondrite samples were excluded with a hand magnet. 10 mg of the powdered sample with 3 mg of Al carrier (WAKO chemical, 1000 mg/l Al, HNO_3 solution) were performed with HF treatment in a Teflon beaker. Mg and Na were removed from Al and Fe fraction by NH_4OH solution. In general, Fe is removed from Al using the cation exchange method, but we removed Fe by KOH to simplify and reduce the time of the purification. The Fe removed was used for AAS measurements to determine Fe contents. The purified Al was acidified by 2N HCl, precipitated as $Al(OH)_3$ with NH_4OH solution and then baked as Al_2O_3 at 900°C. The Al_2O_3 was mixed with an approximate 1:1 amount of silver powder (99.99%, Sigma-Aldrich), and then pressed into cleaned copper cathodes. AMS measurements were performed at the Micro Analysis Laboratory, Tandem Accelerator, University of Tokyo (MALT). To normalize the $^{26}Al/^{27}Al$ ratio, we used standard samples, KN-4 ($^{26}Al/^{27}Al = 7.44{*}10^{-11}$, Nishiizumi, 2004).

The Al, Ca, Mg, Na, Mn, and Ti content in the samples was measured using instrumental neutron activation analysis (INAA). The neutron irradiation for INAA was performed at the research reactor JRR-3M (3.5 MW), Japanese Atomic Energy Agency (JAEA), and gamma-ray counting was performed by the gamma-ray counting system at JAEA.

Fe content was measured by atomic absorption spectrometry (AAS) at Rissho University. Si content was calculated by subtracting the other major chemical compositions from 100%: $SiO_2 = 100 - (FeO + Al_2O_3 + CaO + MgO + Na_2O + MnO + TiO_2)$.

RELATIONSHIP BETWEEN ^{26}Al CONTENT AND MAJOR ELEMENT CONTENT

The results of bulk ^{26}Al content and the major elemental composition of 18 meteorite samples measured in this study are shown in Table 1. Si, Fe, Ni, and S content in chondrites are from Hutchison (2004) because FeNi–metals and sulfides in the chondrite samples were not determined in this study. Table 2 shows the bulk ^{26}Al content and major elemental composition of 19 meteorites from previous literature.

The Al and Si content of the 37 meteorites show a positive linear relation with the ^{26}Al content. However, the other elemental compositions do not. Although the Ca content also shows a positive linear relation to the ^{26}Al content, the ^{26}Al produced by Ca is only about one tenth of that of Si and Al (Leya and Masarik, 2009). The Ca content of stony meteorites ranges from 0.07 to 8% (Hutchison, 2004), and the ^{26}Al content produced by Ca is comparable to the errors of the ^{26}Al content measured by AMS (about 3% of ^{26}Al content). Because the Ca and Al content in meteorites are similar, the relationship between ^{26}Al and Ca content appears to have a linear relationship. We therefore used only the Al and Si content to determine the equation.

The relationship between the ^{26}Al content and the Al and Si content in the 37 meteorite samples are expressed in the following equation based on multiple linear regression analysis:

$$P_{26} = 3.7\,Al + 2.8\,Si \qquad (1)$$

where P_{26} is the calculated ^{26}Al content at the time of meteorite fall and Al and Si are the Al and Si content (%) of the meteorite sample, respectively. The squared multiple relation coefficient adjusted for the degree of freedom (R^2) is 0.98 and the standard error for the calculated ^{26}Al content is 10. The t distribution is 5.6 for Al and 24.9 for Si, respectively.

ESTIMATION OF ^{26}Al CONTENT

Table 3 shows equations calculating P_{26} in this study and in studies by Aylmer *et al.* (1988), Hampel *et al.* (1980), Cressy (1971), and Leya and Masarik (2009). The equation in Table 3 of Leya and Masarik (2009) was converted from their model calculation for a depth of about

Table 4. Comparison of calculated ^{26}Al content by the equation in this study and those of four other studies

Meteorite name	Class	P_{26}				
		This study	Aylmer *et al.* (1988)	Cressy (1971)	Hampel *et al.* (1980)	Leya and Masarik (2009)
		dpm/kg				
Yurtuk	Howardite	87	90	116	97	106
Béréba	Eucrite	96	101	139	107	119
Bouvante	Eucrite	90	94	126	99	111
Haraiya	Eucrite	90	95	134	101	112
Jonzac	Eucrite	92	97	137	103	114
Juvinas	Eucrite	92	97	135	103	114
Millbillillie	Eucrite	91	96	134	101	113
Moore County	Eucrite	88	93	133	99	109
Nuevo Laredo	Eucrite	89	93	131	99	110
Sioux County	Eucrite	90	95	136	101	112
Stannern	Eucrite	89	94	133	100	110
Talampaya	Eucrite	90	95	135	102	112
Aioun el Atrouss	Diogenite	69	67	68	75	80
Bilanga	Diogenite	71	69	70	78	82
Ellemeet	Diogenite	66	64	66	72	77
Garland	Diogenite	73	72	76	79	85
Johnstown	Diogenite	72	70	71	78	83
Johnstown-1	Diogenite	72	70	73	78	83
Johnstown-2	Diogenite	71	69	70	77	82
Roda	Diogenite	68	66	68	74	79
Shalka	Diogenite	73	71	71	80	85
Shalka-05	Diogenite	70	68	68	76	81
Shalka-80	Diogenite	70	68	67	76	81
Tatahouine	Diogenite	82	81	93	90	96
Tatahouine	Diogenite	69	67	66	75	80
Dyalpur	Ureilite	55	54	56	65	64
Haverö	Ureilite	53	51	53	62	61
Novo-Urei	Ureilite	53	51	54	62	61
Angra dos Reis	Angrite	75	79	111	87	93
Allende	CV3	52	53	69	63	63
Lance	CO3.4	49	49	61	60	59
Ningqiang	CK3	49	49	61	57	59
Valera	L5	55	56	72	66	66
Mbale	L5-6	52	52	64	63	62
Kyushu	L6	55	54	61	64	65
Oum Dreyga	H3-5	56	56	66	67	67
Dashoguz	H5	57	56	68	68	67
Difference [%]*		0–29 (10)	0–28 (11)	0–80 (22)	0–45 (14)	0–50 (19)

**The mean values of differences are shown in brackets "( )."*
How = Howardite; Euc = Eucrite; Dio = Diogenite. The elemental composition used for P_{26} calculation of the meteorites is taken from Tables 1 and 2.

60 g/cm^2 in a meteoroid with a radius of about 100 g/cm^2 composed of L chondrites. Table 4 shows P_{26} calculated using the five equations (Table 3) and the measured ^{26}Al content of the 37 meteorite samples. In Fig. 1, we plotted the differences% of the ^{26}Al content calculated by these equations. The "difference%" in Table 4 and Fig. 1 indicates the percentage of relative difference of P_{26} to the measured ^{26}Al contents (^{26}Al); difference% = $\sqrt{(P_{26}-{}^{26}Al)^2}\,/{}^{26}Al \times 100$.

P_{26} *of howardites and eucrites*

The P_{26} of one howardite and 10 eucrite samples, which both have a high Al content (5–7%), were calculated by our equation and agree well with the measured ^{26}Al content (Fig. 1). The P_{26} of the howardite and the eucrite samples calculated using our equation, agree well with measured ^{26}Al more than that of Aylmer *et al.* (1988), which is based on the relationship between ^{26}Al content and the major elemental content of the eucrites samples. The equation of Cressy (1971) gives a too high calcula-

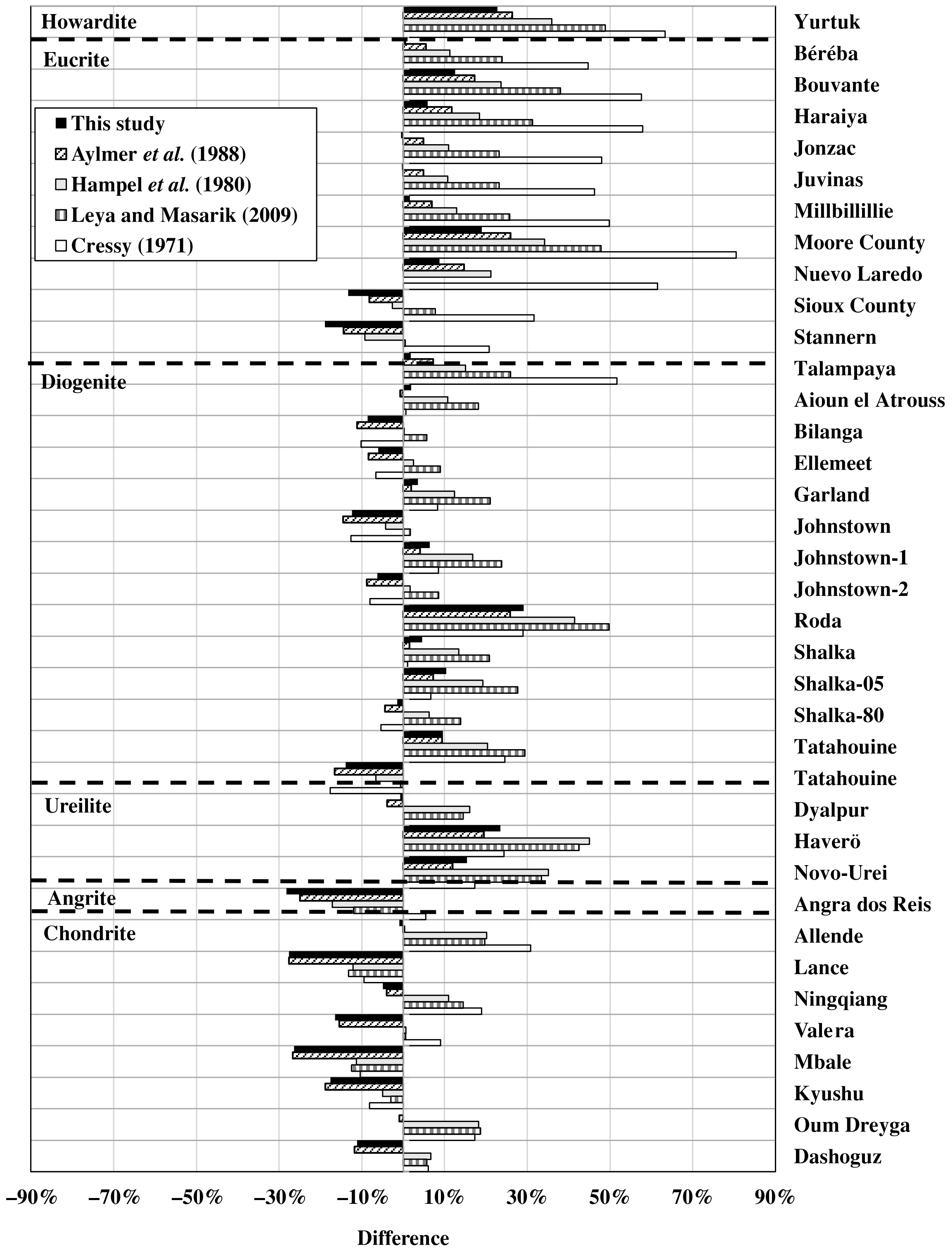

Fig. 1. Difference% between calculated ^{26}Al content and measured ^{26}Al content. The vertical axis shows meteorite names. The horizontal axis shows difference% between measured ^{26}Al content and calculated ^{26}Al content. All measured ^{26}Al content and calculated ^{26}Al content are from Tables 2, 3 and 4, respectively.

tion of P_{26} for the howardite and the eucrites, compared with the measured ^{26}Al content (Fig. 1). These overestimations suggest that the production rate of Al in the equations in previous literature are overestimated, as Al is the main target element for the production of ^{26}Al and is a major element in howardite and eucrite.

P_{26} *of diogenites, ureilites, and angrites*

The P_{26} of 13 diogenites and 3 ureilites, which have a high Mg content (15–24%), were calculated by our equation, Aylmer *et al.* (1988), and Cressy (1971), agree with the measured ^{26}Al contents (Fig. 1). Those of Hampel *et al.* (1980) and Leya and Masarik (2009) tend to be higher than the measured ^{26}Al content (Fig. 1). The ^{26}Al production rate of Mg of Hampel *et al.* (1980) may be overestimated and the equation of Leya and Masarik (2009) does not include Mg. However, the ^{26}Al production rate of Si of Leya and Masarik (2009) may be overestimated.

The P_{26} of angrite calculated by the equations in Table 3 (except Cressy, 1971) are an underestimation. Discussion on this is limited due to there being only one sample of angrite.

P_{26} *of chondrites*

The P_{26} of chondrites calculated using our equation and that of Aylmer *et al.* (1988), tend to be lower than the measured ^{26}Al. The P_{26} of 8 chondrites calculated using the equations of Hampel *et al.* (1980) and Leya and Masarik (2009) agree well with the measured ^{26}Al content of the samples, compared with the P_{26} calculated by the other three equations (Fig. 1). The underestimation of P_{26} calculated by two equations (this study and Aylmer *et al.*, 1988) does not include S and Fe in the equations. ^{26}Al produced from S and Fe may not be negligible in chondrite samples.

SUMMARY

We found our equation to be successful in determining calculation of the ^{26}Al content in howardites, eucrites, diogenites, ureilites compared with the equations in previous literature (Fig. 1). In particular, the P_{26} calculated by our equation agrees well with the measured ^{26}Al content in howardite and eucrite, which have a high Al content. These calculations agree more than the P_{26} calculated by Aylmer *et al.* (1988), which is based on eucrites. Features of our equation are as follows: 1) the production rate of Al for P_{26} is lower than that of previous literature, where the production rate of Al is overestimated and 2) production rates of Mg and Ca are not contained in the equation (the amount of ^{26}Al produced from Mg and Ca is negligible). For chondrite, P_{26} is calculated using the equation of this study and that of Aylmer *et al.* (1988). The P_{26} tend to be lower than the actual ^{26}Al contents. These two equations do not contain S and Fe. This suggests that the amount of ^{26}Al produced by the S and Fe content is not negligible in chondrites.

Acknowledgments—The neutron irradiation experiments were supported by the Inter-University Laboratory for the Common Use of Nuclear Facilities for Joint use of JAEA Facilities. We are grateful to Dr. H. Nagai, Dr. Y. Miura, an anonymous reviewer, and Dr. M. Honda for their helpful reviews.

REFERENCES

Aylmer, D., Herzog, G. F., Klein, J. and Middleton, R. (1988) ^{10}Be and ^{26}Al contents of eucrites: Implications for production rates and exposure ages. *Geochim. Cosmochim. Acta* **52**, 1691–1698.

Cressy, P. J., Jr. (1971) The production rate of ^{26}Al from target element in the Bruderheimc hondrite. *Geochim. Cosmochim. Acta* **35**, 1283–1296.

Dodd, R. (1981) *Meteorites: A Petrologic-Chemical Synthesis*. Cambridge Univ. Press.

Fukuoka, T., Boynton, W. V., Ma, M.-S. and Schmitt, R. A. (1977) Genesis of howardites, diogenites, and eucrites. *Proc. LSC 8th*, 187–210.

Hampel, W., Wänke, H., Hofmeister, H., Spettel, B. and Herzog, G. F. (1980) ^{26}Al and rare gases in Allende, Bereba and Juvinas: implications for production rates. *Geochim. Cosmochim. Acta* **44**, 539–547.

Herpers, U., Vogt, S., Bremer, K., Hofmann, H. J., Suter, M., Wieler, R., Lange, H.-J. and Michel, R. (1995) Cosmogenic nuclides in differentiated Antarctic meteorites: measurements and model calculations. *Planet. Space Sci.* **43**, 545–556.

Hutchison, R. (2004) *Meteorites: A Petrologic, Chemical and Isotopic Synthesis*. Cambridge Univ. Press.

Leya, I. and Masarik, J. (2009) Cosmogenic nuclides in stony meteorites revisited. *Meteor. Planet. Sci.* **44**, 1061–1086.

Leya, I., Lange, H.-J., Neumann, S., Wieler, R. and Michel, R. (2000) The production of cosmogenic nuclides in stony meteoroids by galactic cosmic-ray particles. *Meteor. Planet. Sci.* **35**, 259–286.

Masarik, J. and Reedy, R. C. (1994) Effects of bulk composition on nuclide production processes in meteorites. *Geochim. Cosmochim. Acta* **58**, 5307–5317.

Nishiizumi, K. (1987) ^{53}Mn, ^{26}Al, ^{10}Be and ^{36}Cl in meteorites: data compilation. *Nucl. Tracks Radiat. Meas.* **13**, 209–273.

Nishiizumi, K. (2004) Preparation of ^{26}Al standards. *Nucl. Instr. Meth.* **B223–224**, 388–392.

Welten, K. C., Lindner, L., van der Borg, K., Loeken, T., Scherer, P. and Schultz, L. (1997) Cosmic-ray exposure ages of diogenites and the recent collisional history of the howardite, eucrite and diogenite parent body/bodies. *Meteor. Planet. Sci.* **32**, 891–902.