NON-DESTRUCTIVE MEASUREMENTS OF COSMOGENIC ^{26}Al, NATURAL ^{40}K AND FALLOUT ^{137}Cs IN ANTARCTIC METEORITES

Kazuhisa KOMURA, Masaki TSUKAMOTO and Masanobu SAKANOUE

Low Level Radioactivity Laboratory, Kanazawa University,
Wake, Tatsunokuchi-machi, Nomi-gun, Ishikawa 923–12

***Abstract*:** Non-destructive γ-ray measurements have been made to determine cosmogenic ^{26}Al, natural ^{40}K and fallout ^{137}Cs activities in 15 Antarctic meteorites (14 from Yamato Mountains and 1 from Allan Hills). The ^{26}Al activities range from 72 to 29 dpm/kg. If we assume that the saturation activity of ^{26}Al in chondrites is 60, about 1/3 of the measured meteorites show the contents close to this value; however, the rest show lower values. A simple graphical method was applied to estimate the exposure and terrestrial ages based on ^{26}Al and ^{53}Mn data, and these ages are compared with exposure ages obtained by ^{21}Ne measurements. The results are generally consistent with the ^{21}Ne data. It must be noted that the Antarctic meteorites are highly contaminated with fallout ^{137}Cs derived from nuclear test explosions.

1. Introduction

The measurement of cosmogenic nuclides in Antarctic meteorites offers important information both for meteorite and glacial research. Since most of Antarctic meteorites fell a long time ago and have been buried in the ice sheet, detectable cosmogenic radionuclides are limited to only the long-lived ones, such as ^{14}C ($T_{1/2}=5700$ y), ^{36}Cl ($T_{1/2}=3.1\times10^5$ y), ^{26}Al ($T_{1/2}=7.2\times10^5$ y), ^{10}Be ($T_{1/2}=1.5\times10^6$ y), ^{53}Mn ($T_{1/2}=3.7\times10^6$ y) and some others. Among these, ^{26}Al and ^{53}Mn can be determined rather easily by recent techniques. The ^{26}Al activity is usually determined non-destructively by its 1808 and/or 511 keV γ-rays, using singles or coincidence mode of measurement. On the other hand, ^{53}Mn can be determined sensitively by a neutron activation method. A number of measurements have been made for ^{53}Mn in Antarctic meteorites collected both from Yamato Mountains and Allan Hills (IMAMURA *et al.*, 1979; NISHIIZUMI *et al.*, 1978, 1979, 1980), and ^{26}Al from Allan Hills (EVANS *et al.*, 1979). However, only a small number of data are available concerning ^{26}Al activities in Yamato meteorites.

Since 1979, measurements of radionuclides in meteorite samples have been one of the research works at the Low Level Radioactivity Laboratory, Kanazawa University. Until now 15 Antarctic meteorites and 3 specimens of Kirin meteorite (HONDA *et al.*, 1980, 1982) have been measured. In this report, techniques and results of non-destructive Ge(Li) measurements of ^{26}Al, ^{40}K and ^{137}Cs are described.

2. Experimental

2.1. *Sample*

As a first step of our investigation, rather large Antarctic meteorites ALH-766, Y-7305, -74156 and -74191, were chosen to establish the method of measurement and data analysis. Where ALH stands for Allan Hills and Y for Yamato. Among these, the ^{26}Al activity of ALH-766 has already been measured by EVANS *et al.* (1979). Since our technique was confirmed as reliable by tentative measurements of these samples, we started the measurement of Yamato-74 series meteorites. Meteorites having weights more than 100 g were chosen for the measurement in the order of catalog number compiled by YANAI (1979). They are Y-74001, -74007, -74010, -74011, -74035, -74036, -74037, -74038, -74080, -74082 and -74418. Among these Y-74010, -74011 and -74037 are diogenites and are paired (YANAI, 1979; HONDA, 1981). Since the ^{53}Mn activity in most of these meteorites has already been measured (IMAMURA *et al.,* 1979; NISHIIZUMI *et al.,* 1978, 1979, 1980), ^{26}Al data are considered to be very useful to estimate the terrestrial ages.

2.2. *Fabrication of mockup for detection efficiency calibration*

In order to determine detection efficiency of γ-spectrometer, a mockup sample having the same shape and density as the meteorite must be made for each meteorite sample. For this purpose, usually, a mockup of plaster containing known amount of radionuclides is made to obtain absolute counting efficiency for the meteorite. However, in this work, oil-clay (fat clay) for clay works is used to make a mockup not only because it is easily molded by hand but also because it contains a certain amount of natural radionuclides belonging to the U- and Th-series and ^{40}K which can be used to obtain a counting efficiency curve.

In the case of large meteorites having weights of more than 500 g, the plaster mold for each meteorite was first prepared and then the mockup was fabricated using oil-clay. On the other hand, for small meteorites, a hand-made mockup of oil-clay was prepared directly by comparing carefully the shape with that of the meteorite.

In order to determine the ^{40}K concentration of oil-clay, a disk shaped source (50 mm in diameter and about 50 g in weight) was also prepared from the identical lot of each oil-clay as used for the mockup. Reagent-grade KCl was used as the primary standard for efficiency calibration.

2.3. *Detector system and method of measurement*

The γ-ray detector used is a 80 cc Ge(Li) detector (Ortec 8501-1523S) having energy resolution of 1.8 keV FWHM at 1.33 MeV and detection efficiency of 16% relative to 7.6 cm × 7.6 cm NaI (Tl) detector. In order to reduce the background count due to external γ-rays from the surroundings, the Ge(Li) detector was heavily shielded with 5 cm thick mercury as an inner shield and 20 cm thick iron prepared by cutting the steel rotator of an electric generator fabricated in 1931 (SAKURAI and KOMURA, 1981). The typical background of the Ge(Li) detector is 0.003 cpm/keV at 1808 keV region, and the peak area of 1461 keV γ-ray due to ^{40}K is 0.020 cpm. The spectral data were stored in a full or a half memory of a 4096 channel pulse-height analyzer with the amplifier gain of 0.5 or 1 keV/channel. They were then transferred and stored in floppy disk memory through mini-computer and were analyzed by an automatic peak search program developed by one of the authors (KOMURA, 1972).

The meteorite, and both the mockup and disc-shaped samples made of oil-clay were placed in turn on the end-cup of the Ge(Li) detector to measure the γ-rays emitted from these samples. Counting time required to attain adequate statistical accuracy depends both on the concentration of radionuclides and the geometrical efficiency of each sample. The meteorite sample requires counting time of about 1 week (10000 min) to attain statistical error of less than 5% for the 1808 keV γ-ray from ^{26}Al. On the other hand, mockup and disk samples require about 2 days of measurement to attain 1 to 2% accuracy for the 1461 keV peak due to ^{40}K. The relative efficiency curve was obtained by the counting rates of various γ-rays from ^{214}Pb and ^{214}Bi (daughters of ^{238}U) present in the mockup sample. The accuracy of the counts for major peaks of these nuclides ranged from 2 to 5%, due to the branching ratio of each γ-ray and the energy dependency of intrinsic efficiency of the Ge(Li) detector. Besides these samples, the 1461 keV γ-ray from the KCl standard source was also measured with 1–2% of statistical accuracy to determine absolute K concentration in each oil-clay used for the mockup sample.

2.4. *Determination of counting efficiency*

The K concentration in oil-clay can easily be determined by comparing the count rates of disk samples made from oil-clay and from KCl. The emission rate of the 1461 keV γ-ray from ^{40}K is calculated to be 104.1 γs/min/g-KCl by using the half-life of 1.28×10^9 y, isotopic abundance of 0.0117%, and a γ-ray branching ratio of 10.7% (LEDERER and SHIRLEY, 1978). The absolute counting efficiency of our Ge(Li) detector is $0.85\pm0.01\%$ at 1461 keV for 50 g of disk KCl source (50 mm$\phi\times$13 mm). The γ-ray peaks from ^{214}Pb and ^{214}Bi were used to obtain the relative counting efficiency curve for each mockup source and the absolute counting efficiency was obtained by normalizing the relative efficiency curve at 1461 keV.

The only problem encountered in using mockups of oil-clay is the large differences of solid density between meteorite (ρ=3.3–3.5 g/cm^3 as bulk sample) and oil-clay (ρ=2.0 g/cm^3), which may affect the self-absorption of γ-rays within the sample. Though accurate estimation of self-absorption can only be made by using a mockup having the same factors for shape, density, and chemical composition as those of meteorite, the self-absorption for the meteorite sample was estimated simply by the following method in our study. As a first approximation, the complicated shape of the meteorite was simplified to a cylindrical shape, of which the diameter and thickness can be arbitrarily chosen so as to give the same volume as each meteorite sample. By using this model, self-absorption factors for the two cases, *i.e.* density of 3.3 and of 2.0 g/cm^3, were calculated by a computer code based on a Monte Carlo method. Since the mass attenuation coefficient at 1 to 2 MeV region of γ-ray is approximately the same for most of the materials, mass attenuation coefficient of soil (BECK *et al.*, 1972) was used for the calculation.

3. Results

Typical spectra obtained by non-destructive Ge(Li) measurement are shown in

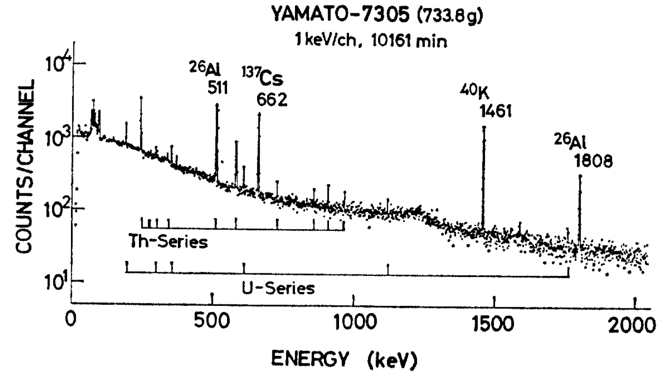

Fig. 1. Ge(Li) spectrum of Yamato-7305. ^{26}Al activity and K content were measured to be 48 dpm/kg and 0.088%, respectively. The γ-ray peak at 662 keV indicates contamination of the meteorite with fallout ^{137}Cs due to nuclear tests in the atmosphere. Other peaks belonging to U- and Th-series nuclides are the background of our detector system.

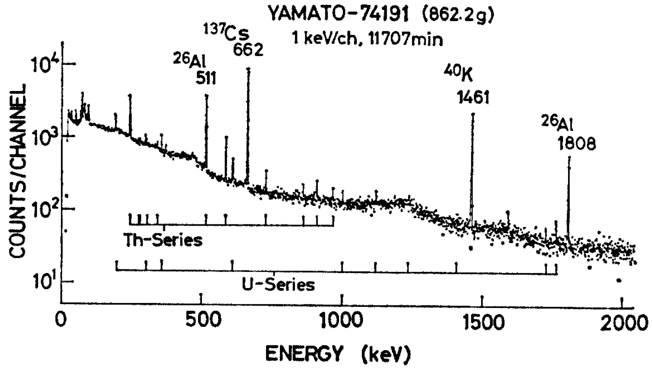

Fig. 2. Ge(Li) spectrum of Yamato-74191. The activity of fallout ^{137}Cs is very high in this meteorite. Count rate of 662 keV peak is 1.774 cpm, which is the highest among the samples measured.

Figs. 1 and 2 for Y-7305 and Y-74191, respectively. As seen in these figures, the 1808 keV peak due to cosmogenic ^{26}Al, and the 1461 keV peak due to natural ^{40}K are clearly observed in the spectra. Besides the 1808 keV γ-ray, the 511 keV γ-ray (annihilation photon) is also emitted from ^{26}Al. The 511 keV peak is clearly seen in the spectra; however, this peak was not used to determine ^{26}Al because the contribution of background to this peak is rather high in our detector system (about half of total counts). The 662 keV peak due to ^{137}Cs ($T_{1/2}=30$ y) shows the contamination of the meteorite with fallout nuclides produced by the nuclear test explosion performed in the atmosphere. The contribution of background is negligibly small for the 1461 keV peak due to ^{40}K for most of the meteorites except the diogenite, in which ^{40}K content is nearly at the detection limit of our detector system. Many other peaks due to U- and Th-series nuclides are in the background of our detector system.

Results of γ-ray measurements are summarized in Table 1 together with the weight and class of each meteorite. The ^{26}Al activities are given as dpm/kg, while ^{40}K activity is converted to % K, where the amount of cosmogenic ^{40}K in stone meteorites is known to be negligibly small for a bulk sample. The ^{137}Cs activity is given in cpm, since this

Table 1. ^{26}Al, ^{40}K and ^{137}Cs activities in Antarctic meteorites measured by non-destructive Ge(Li) measurement.

Sample	Class	Weight (g)	Measuring time (min)	Measured radioactivities		
				^{26}Al (dpm/kg)	^{40}K (%)	^{137}Cs (cpm)
Yamato-7305	L6	733.8	10161	48±4	0.088±.005	0.415±.012
-74001	H5	244.8	10772	38±3	0.067±.004	0.440±.007
-74007	L6	147.3	10830	62±5	0.080±.005	0.267±.007
-74010	Diogenite	275.9	6228	72±5	0.001±.002	0.116±.005
-74011	Diogenite	197.7	12396	61±4	0.001±.002	0.117±.004
-74035	L6	101.0	12533	53±4	0.069±.005	0.263±.006
-74036	L6	195.0	10579	29±3	0.085±.004	0.598±.009
-74037	Diogenite	544.6	5497	66±4	LTD*	0.140±.005
-74038	H5-6	198.4	14523	35±3	0.046±.005	0.354±.006
-74080	L6	236.0	9645	41±3	0.081±.003	0.122±.007
-74082	H4-5	158.6	10244	51±5	0.065±.003	0.439±.010
-74156	H4	707.7	9833	35±3	0.065±.004	0.551±.010
〃		463.5	7441	40±4	0.077±.007	0.234±.007
-74191	L3	862.2	11707	71±5	0.104±.006	1.774±.030
-74418	H6	340.1	10112	38±3	0.061±.003	0.849±.010
Allan Hills-766	H6	562.8	12342	54±4 51±1**	0.086±.005	0.469±.008

* Less than detectable. ** Evans *et al.* (1979).

nuclide is considered to be concentrated only on the surface portion of the meteorite sample.

Errors cited in Table 1 consist both of counting statistics of measurement of the meteorite, the mockup, and the KCl standard, and of systematic errors due to the reproducibility of counting geometry and self-absorption correction. Uncertainties in nuclear data, *i.e.* half-lives, γ-ray branching ratio, and isotopic abundance, etc., are not considered in error calculation.

4. Discussion

4.1. ^{26}Al activity

The cosmogenic nuclide ^{26}Al is produced in meteorites mainly through ^{28}Si(n, $p2n$)^{26}Al and ^{27}Al(n, $2n$)^{26}Al reactions by the interaction of cosmic rays with target silicon and aluminum. The ^{26}Mg(p, n)^{26}Al reaction and spallation reactions of heavier elements also contribute to ^{26}Al production. Since the elemental abundance of silicon and aluminum in chondrite varies only a little not withstanding with the class of the meteorite (38–40% SiO_2 and 2–3% Al_2O_3), the saturation activity of ^{26}Al is considered to be nearly equal. On the other hand, diogenite contains high amount of SiO_2($\sim$50%) and saturation activity of ^{26}Al is expected to be little higher than that of chondrite. The ^{26}Al activities of 45–70 dpm/kg have been observed in stone meteorites soon after fall, and about 60 dpm/kg is commonly accepted as an average saturation activity of ^{26}Al. If the preatmospheric meteorite body is large, low saturation activity in near surface region due to 2π irradiation and in deep layer due to shielding effect must be considered.

As given in Table 1, ^{26}Al activities of Antarctic meteorites measured by the present study ranged from 72 to 29 dpm/kg. Since the ^{26}Al activity data of Y-74156 measured in 1979 was questioned by HONDA (priv. commun., 1982), this sample was remeasured for a smaller specimen. However, new value is consistent with the former one within the counting error. The ^{26}Al activity of 54±4 dpm/kg for ALH-766 agrees well with 51±1 dpm/kg measured by EVANS *et al.* (1979).

Table 1 shows that one-third of the meteorite samples (Y-74007, -74010, -74011, -74037 and -74191) show ^{26}Al activities near the saturation values of 60–70 dpm/kg. Four samples (Y-7305, -74035, -74082 and ALH-766) have ^{26}Al activities of around 50 dpm/kg and the rest (Y-74001, -74036, -74038, -74080, -74156 and -74418) have much lower values. The ^{26}Al and ^{40}K activities of three diogenites (Y-74010, -74011 and -74037) are nearly equal, indicating that they are fragments of the same meteorite body as suggested by mineralogical evidence (YANAI, 1979) and by ^{53}Mn and ^{21}Ne data (HONDA, 1981).

4.2. *Estimation of exposure and terrestrial ages*

Determination of exposure and terrestrial ages of meteorite samples is very useful to investigate the frequency of meteorite fall, spread of a shower, and their accumulation mechanism in special areas in Antarctica, etc. The exposure histories of Antarctic meteorites have been successfully investigated by cosmogenic long-lived nuclides (IMAMURA *et al.*, 1979; NISHIIZUMI *et al.*, 1979), cosmogenic ^{40}K in a magnetic fraction (NITOH *et al.*, 1979), and rare-gas components (TAKAOKA and NAGAO, 1978; NAGAO and TAKAOKA, 1979; TAKAOKA *et al.*, 1981). If the exposure age is sufficiently long as compared with the half-lives of the radionuclides, the terrestrial age can be estimated simply by the ratio of measured to saturation activity. In an ideal case, the terrestrial age can in principle be estimated from the data of a single nuclide with the proper half-life. But this method sometimes leads to erroneous results, therefore data of two or more nuclides must be used to obtain a reliable age. In special cases, however, a complicated exposure history must be considered to explain consistently the measured activities (NISHIIZUMI *et al.*, 1979; IMAMURA *et al.*, 1979).

Since ^{53}Mn data are available for most meteorite samples studied in this work (compiled by HONDA, 1981), estimation of both exposure and terrestrial ages can be made by a simple graphical method described below. In the first step, the ^{26}Al and ^{53}Mn activities were plotted on a logarithmic or linear scale section paper as the activity ratio against their saturation values. Figures 3 and 4 are the examples of the logarithmic case. Here, the saturation activities of ^{26}Al and ^{53}Mn are arbitrarily taken, respectively, to be 60 dpm/kg and 430 dpm/kg-Fe. It is well known that the saturation activities of ^{26}Al and ^{53}Mn depend highly on the size of the preatmospheric body and the depth in it. Therefore, present method is valid only in the case that proper values are taken for saturation activities of ^{26}Al and ^{53}Mn. If the chemical composition of all the meteorite samples is known, it seems better to use ^{26}Al activity normalized by SiO_2 content, just like the case of ^{53}Mn. For simplicity, error is not considered in these values in Fig. 4.

As shown in Fig. 3, the increase of ^{26}Al and ^{53}Mn activities is given by a thick line curve with an arrow. After the meteorite fall, the ^{26}Al and ^{53}Mn activities decrease

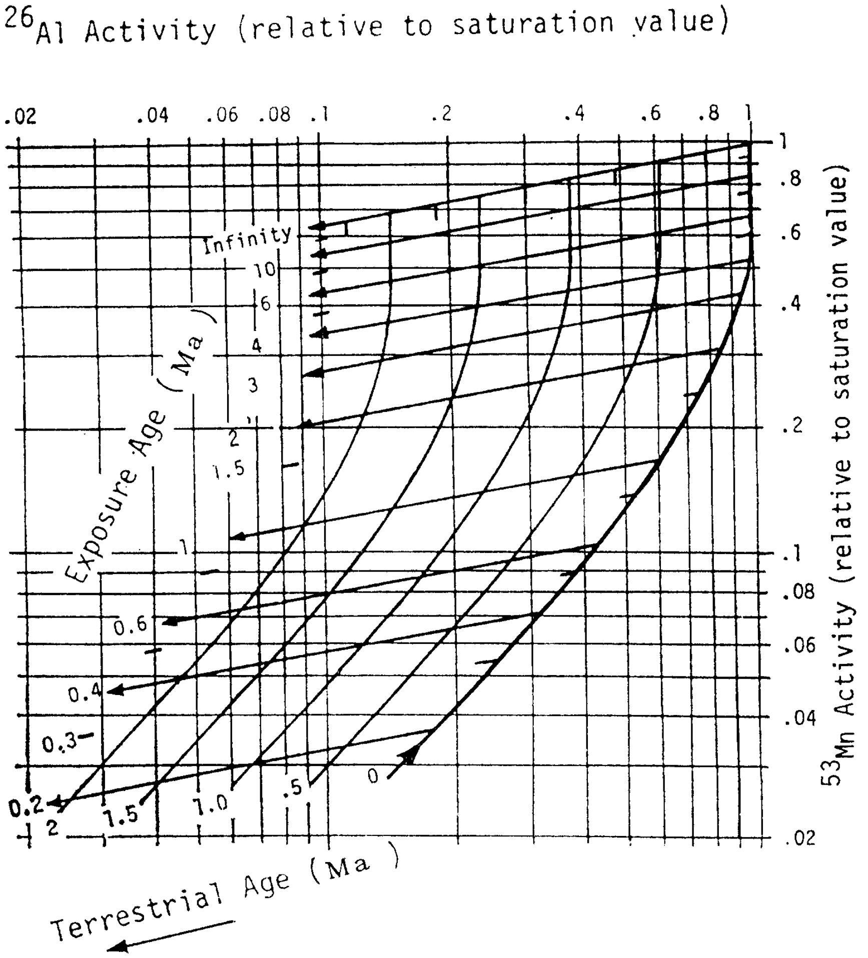

Fig. 3. Growth and decay curves of ^{26}Al and ^{53}Mn activities. The ^{26}Al and ^{53}Mn activities grow along the thick line curve. After the meteorite fall, their activities decrease along the straight line from right to down-left direction. The height of turning point corresponds to the exposure age.

by their own half-lives. If the logarithmic scale is used, the decay of ^{26}Al and ^{53}Mn is given by the straight line from right side to lower-left direction in the figure. The height of the turning point depends on the exposure age. In Fig. 4, the data of Yamato meteorites are shown on the enlarged figure of logarithmic scale. Since Y-74155 and -74156 are paired, ^{53}Mn value of the former is used for Y-74156. The error bar given in the figure accounts only for the statistical error of measurements, while the uncertainty of saturation activities assumed here is not considered for both ^{26}Al and ^{53}Mn. The exposure and terrestrial ages can be estimated easily from the scales given at left and lower part of the figure. In ideal cases, all the data points must be confined by the area surrounded by upper and right-most curves. However, as seen from Fig. 4, Y-74011, -74037 and -74191 data are beyond this area, and Y-74035 seems to have a little lower ^{26}Al activity than that expectable from ^{53}Mn activity. These anomalies may be explained by using the proper value for saturation activities, which will be obtained by considering the depth profile of nuclear interactions in the meteorite body (Imamura *et al.*, 1973; Nishiizumi *et al.*, 1979). If both the ^{26}Al and ^{53}Mn-producing

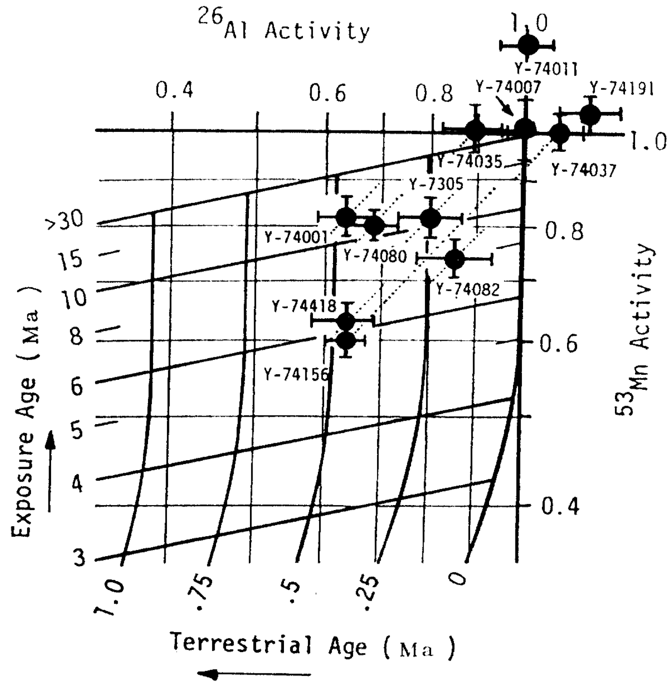

Fig. 4. ^{26}Al-^{53}Mn correlation of Yamato meteorites. The saturation activities of ^{26}Al and ^{53}Mn are arbitrarily taken to be 60 dpm/kg and 430 dpm/kg-Fe, respectively. The exposure and terrestrial ages can be estimated by the graph. The depth effect will be corrected by shifting the point along the dotted lines drawn at an angle of 45 degree.

Table 2. Exposure and terrestrial ages estimated by graphical method.

Sample	Class	Activity (dpm/kg) ^{26}Al ($T_{1/2}$=.72 Ma)	Activity (dpm/kg) ^{53}Mn[a] (3.7 Ma)	Terrest. age (Ma)	Terrest. corr. age	Expos. age (Ma)	Expos. age by other method (Ma)
Adopted saturation value		60	430				
Yamato-7305	L6	48±4	352±18	0.2–.3	(.1)	9–13	22[b]
-74001	H5	38±3	351±16	0.4–.6		11–17	
-74007	L6	62±5	433±19	<0.1		>15	
-74035	L6	53±4	440±19	0.2–.4	(.2)	>15	92[c]
-74036	L6	29±3		0.6–.8			
-74038	H5–6	35±3		0.5–.7			
-74080	L6	41±3	345±15	0.3–.5	(.2)	10–14	49[c], 46[d]
-74082	H4–5	51±5	320±13	0.1–.3		7–9	
-74155	H4		255±15				5[c]
-74156	H4	38±2[e]		0.4–.5	(.5)	5–7	
-74191	L3	71±5	450±23	<0.1	(<.1)	10	12[b]
-74418	H6	38±3	275±11	0.4–.6	(.5)	6–7	7[c], 7[d]
-74010	Diogenite	72±5		<0.1			
-74011	Diogenite	61±4	525±23	<0.1	(<.1)	>15	32[f]
-74037	Diogenite	66±4	445±16	<0.1		>15	
	Averages	68	470	<0.1		>15	
Allan Hills-766	H6	54±4 51±1[g]		0.1–.2	(.1)		16[h]

a: Taken from compiled data by HONDA (1981).
b: TAKAOKA and NAGAO (1978).
c: TAKAOKA *et al.* (1981).
d: NITOH *et al.* (1980).
e: Average of two measurements.
f: NAGAO and TAKAOKA (1979).
g: EVANS *et al.* (1979).
h: SCHULTZ (1978).

reactions have nearly the same depth profile, the correction can be made simply by shifting the point to the lower-left or upper-right direction along the dotted 45° line.

The exposure and terrestrial ages thus estimated are given in Table 2, together with the exposure ages estimated by ^{21}Ne (TAKAOKA and NAGAO, 1978; NAGAO and TAKAOKA, 1979; TAKAOKA *et al.,* 1981; SHULTZ, 1978) and ^{40}K (NITOH, *et al.,* 1980). The corrected terrestrial ages are given in parentheses. As described above, the saturation activities of ^{26}Al and ^{53}Mn are uncertain, therefore, the terrestrial and exposure ages estimated by the graphical method are not quite sure. Y-74007, -74011, -74037 and -74191 are considered to have short terrestrial ages less than 0.1 Ma, since both their ^{26}Al and ^{53}Mn activities are higher than the saturation values assumed here. The exposure ages estimated by the graphical method agree well with other methods for Y-74156 and Y-74418, while rather low values were obtained for Y-7305 and Y-74080 by this method. These differences may be explained by the shielding effect which gives low saturation activity. The terrestrial ages corrected by using exposure ages estimated by other methods become 0.1 and 0.2 Ma for Y-7305 and Y-74080, respectively. The terrestrial age of Y-74156 by the graphical method is estimated to be 0.5 Ma. According to HONDA (priv. commun., 1982), the ^{36}Cl activity measured recently for metal phase of Y-74155 indicates that the terrestrial age must be less than 0.1 Ma. If this value is adopted, the exposure age by the graphical method becomes 15 Ma, which seems inconsistent with the ^{21}Ne data. Y-74036 has the lowest ^{26}Al activity among the measured meteorites, which corresponds to an apparent terrestrial age of 0.7 Ma. Measurements of ^{36}Cl and ^{53}Mn activities and also ^{21}Ne data are strongly required to obtain a reliable age.

As described above, the graphical method is very simple and may be used to estimate roughly relations among exposure and terrestrial ages and shielding simultaneously. This method can be applied to various combination of cosmogenic nuclides, such as ^{26}Al-^{36}Cl, ^{26}Al-^{10}Be, ^{36}Cl-^{10}Be, ^{21}Ne-^{40}K, etc. A three-dimensional expression using ^{36}Cl-^{26}Al-^{53}Mn, ^{26}Al-^{53}Mn-^{21}Ne, etc. will give useful information to investigate complex exposure and terrestrial histories and shielding of meteorite samples.

4.3. Contamination of meteorites with fallout nuclides

A fissiogenic nuclide ^{137}Cs with half-life of 30 y has been scattered on a global scale along with many kinds of fissiogenic nuclides by nuclear explosions performed in the atmosphere during the past three decades. As known from Ge(Li) spectra shown in Figs. 1 and 2, and Table 1, all the meteorites measured are highly contaminated with this nuclide. The ^{137}Cs activity of Y-74191 is the highest and those of three diogenites and Y-74080 are relatively low. The contamination is considered to be limited only to the surface portion unless the meteorite has been considerably weathered. But there seems no apparent correlation between ^{137}Cs activity and surface area (or weight) of meteorite.

Since ^{137}Cs can be detected easily by non-destructive γ-spectrometry, this nuclide can be used as an indicator for the contamination of a meteorite sample with natural and artificial fallout. However, this indicator can be used only for the last three decades because nuclear tests began only about 30 years ago.

Acknowledgments

The authors wish to thank Dr. K. YANAI and the National Institute of Polar Research for providing the Antarctic meteorites. We are grateful to Prof. M. HONDA for encouraging and useful suggestions. We also thank students of our laboratory for their assistance in γ-ray measurements and preparation of mockups.

References

BECK, H. L., DECAMPO, J. and GOGOLAK, C. (1972): In situ Ge(Li) and NaI (Tl) γ-ray spectrometry. Health and Safety Laboratory, HASL-258.

EVANS, J. C., RANCITELLI, L. A. and REEVES, J. H. (1979): ^{26}Al content of antarctic meteorites: Implications of terrestrial ages and bombardment history. Proc. Lunar Planet. Sci. Conf. 10th, 1061–1072.

HONDA, M. (1981): Terrestrial history of Antarctic meteorites recorded in the cosmogenic nuclides. Geochem. J., **15**, 163–181.

HONDA, M., HORIE, K., IMAMURA, M., NISHIIZUMI, K., TAKAOKA, N. and KOMURA, K. (1980): Irradiation history of the Kirin meteorite. Geochem. J., **14**, 83–89.

HONDA, M., NISHIIZUMI, K., IMAMURA, M., TAKAOKA, N., NITOH, O., HORIE, K. and KOMURA, K. (1982): Cosmogenic nuclides in the Kirin chondrite. Earth Planet. Sci. Lett., **57**, 101–109.

IMAMURA, M., FINKEL, R. C. and WAHLEN, M. (1973): Depth profile of ^{53}Mn in the lunar surface. Earth Planet. Sci. Lett., **20**, 107–112.

IMAMURA, M., NISHIIZUMI, K. and HONDA, M. (1979): Cosmogenic ^{53}Mn in Antarctic meteorites and their exposure history. Mem. Natl Inst. Polar Res., Spec. Issue, **15**, 227–242.

KOMURA, K. (1972): Kô-bunkainô γ-sen supekutoru no jidô kaiseki puroguramu (Automatic peak search program of high resolution γ-ray spectrum). Institute for Nuclear Study, Univ. of Tokyo, INS-TCH-7.

LEDERER, C. and SHIRLEY, V. S. (1978): Table of Isotopes. 7th ed. New York, John Wiley.

NAGAO, K. and TAKAOKA, N. (1979): Rare gas studies of Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 207–220.

NISHIIZUMI, K., IMAMURA, M. and HONDA, M. (1978): Cosmic ray induced ^{53}Mn in Yamato-7301(j), -7305(k) and -7304(m) meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 209–219.

NISHIIZUMI, K., IMAMURA, M. and HONDA, M. (1979): Cosmic ray produced radionuclides in Antarctic meteorites, Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 161–177.

NISHIIZUMI, K., MURRELL, M. T., ARNOLD, J. R., IMAMURA, M. and HONDA, M. (1980): Cosmogenic ^{53}Mn survey of Yamato meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **17**, 202–209.

NITOH, O., HONDA, M. and IMAMURA, M. (1980): Cosmogenic K-40 in Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **17**, 189–201.

SAKURAI, J. and KOMURA, K. (1981): Secular change of background activity in Ge(Li) detector. Radioisotopes, **30**, 471–474.

SCHULTZ, L. (1978): Abstract. The 41st Ann. Meeting Meteoritical Soc., Aug. 14–17, 1978, Sudbury, Canada.

TAKAOKA, N. and NAGAO, K. (1978): Rare gas studies of Yamato-7301 (j), -7304 (m) and -7305 (k). Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 198–208.

TAKAOKA, N., SAITO, K., OHBA, Y. and NAGAO, K. (1981): Rare gas studies of twenty-four Antarctic chondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 264–275.

YANAI, K., comp. (1979): Catalog of Yamato Meteorites. 1st ed. Tokyo, Natl Inst. Polar Res., 188 p. with 10 pls.

(Received June 12, 1982; Revised manuscript received August 23, 1982)