COSMOGENIC ^{53}Mn SURVEY OF YAMATO METEORITES

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***Abstract*:** As part of a program to compile statistical information on the cosmic ray exposure history of meteorites, cosmogenic ^{53}Mn ($t_{1/2}=3.7\times10^6$y) was determined in twenty-one Yamato meteorites. Yamato-74116 and -74193 contain especially low amounts of ^{53}Mn suggesting short cosmic ray exposure ages. The ^{53}Mn activity level of Yamato-74192 is 578 ± 24 dpm/kg (Fe+1/3 Ni) which is the highest value we have ever measured in a chondrite to date. Although the recovered mass of Yamato-74159 was small, its ^{53}Mn content indicates a large preatmospheric mass. Two histograms, which illustrate the frequencies of the ^{53}Mn contents of chondrites from Antarctica and those of chondrites from other parts of the world, show similar statistical distributions. This indicates that the terrestrial ages of Antarctic meteorites are generally short (<1 my) in comparison to the ^{53}Mn half-life.

1. Introduction

A large number of meteorites returned from Antarctica provide an opportunity for increasing our knowledge in all areas of meteorite research. Work done with cosmogenic nuclides in these objects has shown terrestrial ages to lie in the range of 10^4 to 10^6 years (FIREMAN, 1979, 1980; NISHIIZUMI *et al.*, 1979b, 1980b). Such terrestrial ages have but a small effect on the activity levels of ^{53}Mn ($t_{1/2}=3.7\times10^6$ y) in the recovered meteorites. In addition, studies of magnetic and non-magnetic separates have shown weathering to have little effect on the ^{53}Mn content (IMAMURA *et al.*, 1979). It appears then that Antarctic meteorites can be used to compile statistics concerning the ^{53}Mn content of meteorites. Such information is of interest in regards to possible variations of ^{53}Mn production during past history and/or with meteorite type.

In this study, ^{53}Mn is determined in 21 Yamato meteorites (mainly the 74–75 series). These values are compared with previous results in meteorites from Antarctica and from other parts of the world.

2. Experimental and Results

In this work ^{53}Mn was determined by neutron activation analysis (MILLARD, 1965) using 0.5–0.8 g of meteorite. The experimental procedures were essentially the same as in our previous work (*e.g.* IMAMURA *et al.*, 1973). The purified Mn extracts were irradiated in the BG-7–6 hole of the JRR-3 reactor of the Japan Atomic Energy Institution, Tokai, Ibaraki. The total thermal neutron fluence (530 hours) was 5.0×10^{18} n/cm^2 as determined by the monitor reaction ^{59}Co(n, γ) ^{60}Co, $\sigma=37b$. The ^{54}Mn ($t_{1/2}=312$ days) counting was performed using a well-type 3″ NaI (Tl)

Table 1. Results on neutron activation analysis of ^{53}Mn.

Yamato meteorite	Sample description			Sample counted after irradiation			After[3)] (n, p), $(n, 2n)$ correction cpm/mg Mn	dpm[4)] ^{53}Mn/kg Fe
	wt (mg)	Mn (ppm)	Fe (%)	Fe (μg)	Mn (μg)	^{54}Mn[2)] (cpm)		
-74011,94	751.4	4580	13.3	0.55	2573	14.60±.11	4.51±.11	526±23
-74077	620.9	2730	21.4	0.45	1407	17.07±.12	10.96±.20	474±20
-74080	606.4	3040	18.9	0.44	1459	11.14±.10	6.46±.13	352±15
-74081,94	632.8	2490	25.7	0.37	1313	15.17±.12	10.38±.20	341±14
-74082	563.9	2530	25.7	0.49	1171	12.87±.11	9.87±.19	327±14
-74116,93	733.8	2770	23.1	0.75	1577	4.340±.058	1.576±.058	64±3
-74159	459.2	4470	14.7	0.66	1646	10.18±.08	5.01±.11	516±22
-74192,85	769.7	2630	29.0	0.33	1541	31.52±.23	19.29±.34	593±24
-74193	654.5	2380	26.2	0.47	1327	10.58±.08	6.80±.14	209±9
-74364	593.1	2470	29.1	0.45	1219	15.79±.11	11.78±.22	339±14
-74374,93	763.6	2340	29.4	0.77	1389	17.84±.11	11.67±.21	315±13
-74418	661.7	2380	27.3	0.65	1327	14.22±.10	9.54±.18	282±12
-74454	697.9	2660	24.6	0.41	1512	18.09±.16	10.79±.21	396±17
-74663,94	607.1	2530	21.9	0.41	1368	10.75±.10	6.69±.14	262±11
-75028	715.1	2370	25.2	0.47	1424	12.51±.09	7.61±.15	243±10
-75097	629.7	2690	21.8	0.67	1450	16.71±.12	10.35±.19	433±18
-75102	502.0	2570	22.4	0.36	1138	14.85±.14	11.88±.23	462±19
-75108	621.0	2800	21.4	0.38	1483	15.61±.13	9.36±.18	415±17
-75258	621.6	2710	20.8	0.34	1426	13.18±.12	8.07±.16	356±15
-75271	627.8	2770	21.1	0.50	1444	15.71±.14	9.71±.19	432±18
-691-a	34.1	287[1)]	72.6	1.18	50.2	1.156±.038	21.20±.81	189±10
-691-b	41.4	290[1)]	82.0	0.90	53.6	1.525±.043	26.81±.89	186±9

Table 1 (Continued).

^{53}Mn standard	Solution (g)		Fe (μg)	Mn (μg)	^{54}Mn[2] (cpm)	^{54}Mn (cpm/mg Mn)	After[3] (n, 2n) correction cpm ^{54}Mn/ mg Mn	cpm ^{54}Mn/ dpm^{53}Mn
^{53}Mn-1	0.2320	0.781 dpm ^{53}Mn/mg Mn	0.23	278.7	64.58±.23	231.7±3.6	230.5±2.6→	295.1±3.3
^{53}Mn-2	0.2163		0.35	270.2	62.58±.20	231.6±3.6		
^{55}Mn standard	**Mn metal (mg)**					**cpm ^{54}Mn/ mg Mn**		
^{55}Mn-1	6.7		0.15	6323	7.448±.115	1.177±.025	1.163±.017	
^{55}Mn-2	8.1		0.17	7590	8.750±.101	1.152±.022		
Fe standard	**Fe metal (μg)**	**Chemical yield (%)**				**cpm ^{54}Mn/ μg Fe**		
Fe-1	451	77.7			10.04±.21	0.0287±.0007	0.0285±.0005	
Fe-2	311	70.7			6.22±.10	0.0283±.0006		

1) Total Mn(μg) including carrier: 65.3 (a); 69.6 (b).

2) Weighted averages of at least two counting periods. All activities have been corrected to October 26, 1979, the end of irradiation. The uncertainties are 1σ counting statistics.

3) A 1.5% uncertainty for the Mn yield and the uncertainty in the ^{55}Mn(n, 2n) ^{54}Mn correction have been added quadratically to the counting error.

4) The following uncertainties have been added quadratically: 2.5% for Mn concentration; 2.5% for Fe concentration and percentage uncertainty from the previous column. The 5% uncertainty in the original standardization of the ^{53}Mn standard has not been included.

detector coupled with GM anticoincidence counters. The counting efficiency was 20.4% for the ^{54}Mn photopeak (835±55 keV) with a background of 2.64 cpm. The detailed data for the neutron activation of ^{53}Mn are presented in Table 1. The concentrations of Mn, Fe, Co and Ni in the meteorites were determined by atomic absorption spectroscopy and neutron activation analysis using a TRIGA-II reactor at Musashi-Kogyo University. Data from the two methods agree within error. The atomic absorption results are presented in Tables 1 and 2. The recovered meteorite mass, and the ^{53}Mn results are given in Table 2. In the last column, the specific activities of ^{53}Mn in Fe have been corrected for a small contribution from Ni. The production rate of ^{53}Mn in Ni relative to that in Fe is estimated to be 1/3 (NISHIIZUMI, 1978).

Table 2. ^{53}Mn contents found in Yamato meteorites.

Yamato meteorite	Class	Recovered mass (kg)	Co (ppm)	Ni (%)	Fe/Mn	dpm ^{53}Mn/kg[1)] (Fe+1/3 Ni)
-74011,94	Diog.	0.21	31	≦0.02	29	525±23
-74077	L	5.58	560	1.21	78	465±19
-74080	L6	0.54	430	1.25	62	345±15
-74081,94	H5	0.10	860	1.79	103	333±14
-74082	H5-4	0.18	870	1.79	102	320±13
-74116,93	(L)	0.07	690	1.32	83	63±3
-74159	Eucr.	0.10	7	≦0.01	33	516±22
-74192,85	H6	0.42	1100	2.18	110	578±24
-74193	H4-5	1.82	850	1.74	110	205±9
-74364	H4-5	0.76	1010	1.91	118	332±14
-74374,93	H6	0.21	1000	1.92	126	308±13
-74418	H6	0.57	1000	1.90	115	275±11
-74454	L5	0.58	890	1.72	93	387±16
-74663,94	L6	0.21	680	1.67	87	255±11
-75028	H3-4	6.10	790	1.81	106	237±10
-75097	L4-5	2.57	620	1.29	81	424±18
-75102	L6	11.0	710	1.42	87	452±19
-75108	L4-5	0.59	600	1.30	76	407±17
-75258	LL6	0.97	560	1.22	77	350±15
-75271	L6	1.80	580	1.20	76	424±18
-691-a	E3-4	0.72	3510	6.48	2530	184±10
-691-b	(metal phase)		3960	7.54	2830	180±9

1) As a member of targets, we have included Mn in our previous papers. Because the contribution from Mn is always much smaller than the experimental uncertainty, it has been neglected in this paper.

3. Discussion

Of the twenty-one meteorites studied in this work, only two have been investigated for rare gases. The rare gas exposure age of Yamato-74159 is reported to be 32 my (10^6 y) (KAMAGUCHI and OKANO, 1979). Therefore, the measured content of 516±22 dpm ^{53}Mn/kg (Fe+1/3 Ni) in this meteorite is equal to the saturation value. This high ^{53}Mn activity level suggests that the preatmospheric size of Yamato-74159 was relatively large, even though the recovered mass was small and the specimen appeared to be a nearly complete, individual object (YANAI, 1979).

According to SHIMA *et al.* (1973), the cosmogenic ^{21}Ne in Yamato-691 is 0.78×10^{-8} cc STP/g with ^{3}He/^{21}Ne=3.36 and ^{22}Ne/^{21}Ne=1.109. The low ^{3}He/^{21}Ne ratio relative to ^{22}Ne/^{21}Ne is a typical feature of Antarctic meteorites (WEBER and

SCHULTZ, 1980). SHIMA *et al.* (1973) calculated the exposure age for Yamato-691 to be 1.7 my, using a high ^{21}Ne production rate ($P_{21}=0.46\times10^{-8}$ cc STP/g my). Based on the method of HERZOG and ANDERS (1971), the effects of chemical composition were normalized using the published analytical data for Yamato-691 (SHIMA *et al.*, 1973) and the average composition of L chondrites (MASON, 1971); the exposure age is recalculated to be 2.1 my. Using this exposure age, the ^{53}Mn saturation value is estimated to be 570 dpm/kg (Fe+1/3 Ni). Based on a lower reference production rate of $P_{21}=0.31\times10^{-8}$ cc STP/g my (L chondrites with $^{22}Ne/^{21}Ne=1.11$) (NISHIIZUMI *et al.*, 1980a), the exposure age is calculated to be 3.0 my. The ^{53}Mn exposure age estimated, using the measured ^{53}Mn content and the $^{22}Ne/^{21}Ne$ ratio, is 3.1 my. These two ages agree well with each other.

Cosmic ray produced ^{40}K ($t_{1/2}=1.28\times10^{9}$ y) from the metal phase of Yamato-74080, -74192 and -74663 has been determined by NITOH *et al.* (1980). The ^{40}K exposure ages obtained were 46 ± 2, 33 ± 2 and 14 ± 1 my, respectively. Using these data, the ^{53}Mn saturation values are calculated to be 345 ± 15, 578 ± 24 and 275 ± 26 dpm/kg (Fe+1/3 Ni). The ^{53}Mn activity level of Yamato-74192 is the highest value we have ever measured in a chondrite. This production rate is nearly the maximum level expected for ^{53}Mn in a chondritic body. Yamato-74192 appears, therefore, to have been irradiated by cosmic rays in the deep region of a preatmospheric body with a radius of 40–50 cm. On the other hand, Yamato-74080 and -74663 have low saturation ^{53}Mn values suggesting these meteorites were either of small preatmospheric size (10–15 cm) or located in the near-surface region of the body.

In Fig. 1 the ^{53}Mn contents of the eighteen Yamato ordinary chondrites determined in this work as well as those of additional thirty Antarctic ordinary chondrites (Yamato and Allan Hills) previously studied (IMAMURA *et al.*, 1979; NISHIIZUMI *et al.*, 1978, 1979a, 1980b) are displayed in a histogram. For comparison the ^{53}Mn distribution of eighty-two ordinary chondrites recovered from other parts of the world (BHATTACHARYA, 1979; ENGLERT and HERR, 1978; FRUCHTER *et al.*, 1978; NISHIIZUMI, 1978) is also shown. These values have not been corrected for undersaturation. The two distributions are very similar, which indicates that the terrestrial ages of Antarctic meteorites are generally short (≤1 my) compared to the half-life of ^{53}Mn (3.7 my). This is supported by recent ^{14}C ($t_{1/2}=5740$ y) and ^{36}Cl (3.0×10^{5}y) measurements for Antarctic meteorites whose terrestrial ages are found to be between 10^{4} and 10^{6} y. Currently the lower limit is set by a terrestrial age of 1.0×10^{4} years for ALHA77256 and the upper limit is set by an age of 7.2×10^{5} years for ALHA-77002 (FIREMAN, 1979, 1980; EVANS *et al.*, 1979; NISHIIZUMI *et al.*, 1979b, 1980b). A histogram of the ^{26}Al ($t_{1/2}=7.2\times10^{5}$ y) contents of Antarctic meteorites is in fact shifted toward lower values as compared to contemporary samples (EVANS *et al.*, 1979). This is due simply to the difference in half-lives. Fig. 1 indicates that ^{53}Mn measurements in Antarctic meteorites can, in most cases, be used for the study of meteorite irradiation histories without necessarily correcting for terrestrial age.

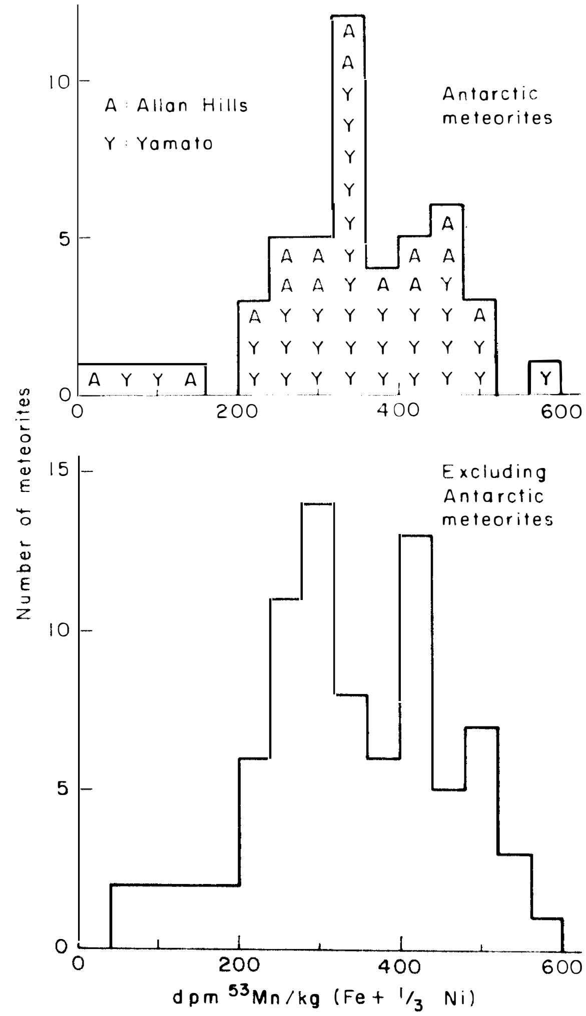

Fig. 1. Histograms of ^{53}Mn contents in 48 Antarctic ordinary chondrites and in 82 other ordinary chondrites.

In addition, studies of magnetic and non-magnetic separates have also shown weathering to have little effect on the ^{53}Mn content (IMAMURA *et al.*, 1979; NISHIIZUMI *et al.*, 1980a).

In Fig. 1, ^{53}Mn levels below about 350 dpm/kg (Fe+1/3 Ni) indicate meteorites of small preatmospheric size and/or short cosmic ray exposure ages. Short exposure ages are likely especially for those objects with ^{53}Mn below 250 dpm. The similarity between the histograms of ^{53}Mn in Antarctic meteorites and other, more contemporary meteorites suggests that the distribution of exposure ages for chondrites during the last few million years is comparable to that of recent falls.

In the previous studies (IMAMURA *et al.* 1979; NISHIIZUMI *et al.*, 1978, 1979a, b), we found two Antarctic meteorites, Yamato-7301 and Allan Hills-768, which had experienced a multi-stage irradiation in space. Both meteorites have large discrepancies between the low radioactivity levels and the relatively high contents of stable cosmogenic nuclides. In this work, we found low ^{53}Mn levels in Yamato-74116 and -74193. Yamato-74116 has an especially low value (63 ± 3 dpm ^{53}Mn/kg (Fe+ 1/3 Ni)) which suggests an exposure age less than 1 my, assuming a simple exposure history. The determination of other radioactivities (*e.g.*, ^{10}Be, ^{26}Al and ^{36}Cl) and stable nuclides would provide additional information concerning the exposure history of this meteorite. However, the determination of ^{53}Mn in a number of samples presented by this work and other such studies does provide important statistical information concerning the cosmic ray exposure history of meteorites.

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