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Fig. 1

Figure 1: Fig. 1

Abstract

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PRODUCTS OF COSMIC RADIATION IN THE SIKHOTE-ALIN METEORITE

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The investigation of the products of cosmic reactions in the iron Sikhote-Alin meteorite is a continuation of our work on the study of isotopes of inert gases in stony meteorites (^{1}). In both stony and iron meteorites, inert gases have one and the same source of origin, being products of deep-spallation reactions (^{2}-^{7}). However, the interpretation of experimental data in the case of stony meteorites is complicated by the complexity of their chemical composition. Iron meteorites have a simpler chemical composition and therefore are a more valuable object for study. We were interested in the following questions: 1) the study of the relative content of the isotopes of light inert gases (He, Ne, A) in individual samples of the meteoritic shower; 2) the investigation of the change in the content of cosmogenic products with depth in a separate large specimen. The principal object selected was specimen No. 2093 of the Sikhote-Alin meteorite.

Fig. 1

To clarify the question of the change in the content of inert-gas isotopes with depth and to detect a possible maximum, which could be expected from calculated data (^{8}), a core was taken from the body of meteorite No. 2093 in the direction normal to the surface, which was covered with large regmaglypts. The length of the core was 24 cm, the diameter 5.7 cm. The core material was converted into shavings, with samples collected separately at distances of 0.6 cm from one another. In this type of processing, in each of the layers a certain amount of dust was obtained, enriched in troilite and schreibersite as the more brittle inclusions. Subsequently all these fractions were mixed and investigated (sample V). To extract the inert gases, the samples were melted in a previously degassed graphite crucible by high-frequency currents. The details of the vacuum apparatus for purification and the procedure for measuring the evolved gases have been described by us (^{1}).

The results of the analyses are given in Table 1 and in Fig. 1. Examination of the results shows that no monotonic change in the content of cosmogenic products with depth is observed. Nor is there the presence of a flat maximum, which has repeatedly been mentioned ([8], [9]). Subst–

Table 1

Sample Nos.	a^1, cm	A^{40}	A^{38}	A^{36}	A^{38}, 10^{-7} cm^3/g	A^{36}, 10^{-7} cm^3/g	$\frac{A^{38}}{A^{36}}$	He, 10^{-6} cm^3/g	He^4, 10^{-6} cm^3/g	He^3, 10^{-6} cm^3/g	$\frac{\text{He}^3}{\text{He}^4}$	Ne, 10^{-8} cm^3/g	Ne^{20}, 10^{-8} cm^3/g	Ne^{21}, 10^{-8} cm^3/g	Ne^{22}, 10^{-8} cm^3/g	$\frac{A^{38}}{\text{Ne}^{21}}$	$\frac{\text{He}^3}{A^{38}}$	$\frac{\text{He}^3}{\text{Ne}^{21}}$
1[3]	0.4							5.90	4.75	1.15	0.26			1.0	4.1			115
3	1.2	24.4	1.50	1.00	0.39	0.24	1.62	5.40	4.40	1.00	0.23						26	
4	1.8	10.9	1.16	1.00	0.48	0.30	1.58	4.92	3.92	1.00	0.25	2.7	1.4	0.7	0.6	6.8	21	143
5	2.4	22.4	1.50	1.00	0.50	0.31	1.61	6.15	5.20	0.95	0.18	3.2	1.1	1.0	1.1	5.0	19	86
8	4.2	38.0	1.33	1.00	0.46	0.30	1.50	5.00	4.17	0.83	0.20	1.4	0.4	0.5	0.5	9.2	18	166
11	6.0							6.76	5.50	1.26	0.23							
12	6.6	19.9	1.51	1.00	0.52	0.32	1.60	5.80	4.89	0.91	0.19	2.4	0.9	0.7	0.8	7.4	18	130
13/14	7.7	32.5	1.51	1.00	0.91	0.54	1.68	8.17	6.57	1.60	0.24	4.3	1.9	1.1	1.3	8.3	18	145
15	8.8	17.2	1.53	1.00	0.60	0.37	1.62	6.75	5.53	1.22	0.22	3.5	1.2	1.1	1.2	5.5	20	111
16	9.6	24.5	1.58	1.00	0.65	0.38	1.71	8.20	6.77	1.43	0.21	7.5	2.6	2.3	2.6	2.5	22	62
17	10.3	20.4	1.54	1.00	0.66	0.40	1.61	7.15	5.86	1.29	0.22						20	
23	13.9	25.0	1.46	1.00	0.40	0.25	1.60	5.14	4.14	1.00	0.24						25	
24	14.5	17.8	1.51	1.00	0.56	0.35	1.60	6.30	5.18	1.12	0.22	3.2	1.5	0.8	0.9	7.0	20	140
27	17.0							7.20	5.70	1.50	0.26			1.4	1.7			107
30	18.3	23.6	1.50	1.00	0.63	0.39	1.61	5.80	4.70	1.10	0.24						20	
35	21.6	50.6	1.29	1.00	1.16	0.77	1.52	9.73	7.61	2.12	0.28	5.6	2.0	1.8	1.8	6.5	18	118
37	22.8	20.0	1.49	1.00	0.56	0.36	1.58	6.06	5.00	1.06	0.22						19	
I[4]		21.0	1.55	1.00	0.70	0.42	1.67	6.55	5.38	1.17	0.22	3.0	1.1	0.9	1.0	7.8	17	130
II[5]		68.2	1.44	1.00	0.59	0.32	1.81	6.28	5.03	1.25	0.25	3.6	1.5	1.1	1.0	5.4	21	113
III[6]		32.6	1.52	1.00	0.75	0.45	1.69	8.00	6.30	1.70	0.27	3.6	1.4	1.1	1.1	6.8	23	155
IV[7]		32.7	1.56	1.00	0.80	0.46	1.73	7.86	6.20	1.66	0.27	5.2	1.9	1.7	1.6	4.7	22	98
V[8]		52.0	1.33	1.00	1.00	0.64	1.58	12.0	9.90	2.10	0.22	15.5	5.1	4.9	5.5	2.0	21	43
2052		93.2	1.14	1.00	0.38	0.24	1.60	3.75	3.00	0.75	0.24	2.0	0.8	0.6	0.6	6.3	20	125
7035		182	0.84	1.00	0.25	0.15	1.73	2.28	1.84	0.44	0.24			0.4		6.3	18	110
7159		198	0.56	1.00	0.028	0.021	1.33	0.49	0.42	0.07	0.16						25	

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[1] a –distance from the surface of the meteorite.

[2] Ratio of the corrected values of A^{38} and A^{36}, considering practically all A^{40} to be atmospheric.

[3] Samples from No. 1 to V belong to specimen No. 2093.

[4] Average sample; shavings obtained in drilling out the core; the average values from 5 experiments are given.

[5] Layers Nos. 2, 10.

[6] Layers Nos. 6, 7, 9, 19, 24, 26, 28, 31, 32, 33.

[7] Layers Nos. 34, 38.

[8] Powder enriched in troilite and schreibersite.

the existence of this maximum is generally doubtful, if one takes into account that the primary particles are distributed over an energy spectrum of a power-law character. Maxima for different energies will occur at different depths, which will completely smear out the overall curve. A preliminary calculation based on the data of Fireman' s work (⌒10) shows the absence of a maximum on the curve.

The content of cosmogenic products, as shown in Table 1, varies on average by a factor of 15-20 between the richest and the poorest samples. Obviously, samples with a low content of cosmogenic products belong to the deep layers of the meteorite. Assuming that the radius of the fallen meteorite before its final fragmentation was approximately 100 cm, one may calculate the mean absorption length, which turns out to be equal to 280 g/cm^2. The value obtained corresponds to the mean absorption length of the star-producing component in dense substances (for carbon 166 g/cm^2, for aluminum 200 g/cm^2, for lead 350 g/cm^2 (⌒11)). Investigation of a larger number of individual meteorite samples will refine the value obtained, apparently in the direction of decreasing it.

Let us consider the data of Table 1. In the case of argon the cosmogenic isotopes are A^{38} and A^{36}. A^{40} enters the vacuum apparatus from the air and is an unavoidable contaminant. The content of K^{40} in iron meteorites is too negligible to explain even a small part of the A^{40} found. The mean ratio $A^{38}/A^{36} = 1.62$. The larger yield of nuclei at isobar 38 relative to the yield of nuclei at isobar 36 is caused by the decrease in the number of nucleons that must be removed from the iron nucleus, and also by the different distance of the nuclei from the bottom of the valley of stability.

For neon, as in the case of stony meteorites (⌒1), an approximately equal content of all three stable isotopes is characteristic. The mean ratio A^{38}/Ne^{21} for several samples is 6.8. This value may be compared with the ratio of the number of stars giving, as the residual nucleus, respectively A^{38} and Ne^{21}. To obtain A^{38} and Ne^{21} nuclei from an Fe^{56} nucleus, it is necessary to remove respectively 18 and 35 nucleons. On the basis of the work of Lanius (⌒12) one may assume that stars associated with the formation of A^{38} and Ne^{21} will contain, respectively, 6-7 and 13-14 shower particles. The ratio of the number of stars with 6-7 rays to the number of stars with 13-14 rays at high altitudes is 6.5 (⌒13, ⌒14). The relative yield of A and Ne isotopes makes it possible to estimate the energy of the primary particles (⌒15, ⌒16), which turns out to be equal to 1000 MeV. The value found is somewhat smaller than the accepted mean energy of cosmic particles.

The helium isotopes He^4 and He^3 are mainly evaporation particles, and only a small part of them is produced by fragmentation. The variations in the ratio He^3/He^4, generally speaking, go beyond the limits of experimental error. Evidently, these variations should be explained by a not quite uniform distribution of radioelements in the meteorite, which give a greater or lesser background of radiogenic He^4. The value of the ratio He^3/He^4 is characteristic for sample No. 7159. With the overall low helium content (which determines the assignment of sample No. 7159 to the deep layers of the meteorite), the radiogenic background evidently begins to show itself here; for the other samples it is not of significant importance. Taking the ratio $(He^3 + H^3)/He^4$_k = 0.3, where He^4_k is the cosmogenic part of He^4, we obtain a value of $0.2 \cdot 10^{-6}$ cm^3/g for the mean content of radiogenic helium in the meteorite. Another possible explanation for the relative decrease in the He^3 content in this sample may be that the mean energy of the incident particles is lower, and correspondingly the relative yield of α-particles is higher.

As is not difficult to see from Fig. 1 and Table 1, some subsamples of sample No. 2093 give an increased content of cosmogenic products. It was noticed that these subsamples coincide with those portions of the meteorite where inclusions of troilite FeS and schreibersite $(Fe, Ni,Co)_3P$ are most highly developed.

To establish the dependence between the content of light elements and the content of cosmogenic products, a chemical analysis of several samples* was carried out. The results are given in Table 2. The increase in the content of neon isotopes, for example in sample V, is not surprising. The cross section for the formation of neon from light nuclei (S, P) is greater than the cross section for the formation of the same isotopes from iron nuclei. More complicated is the explanation of the increase in the content of cosmogenic argon isotopes in the same regions, since neither phosphorus nor sulfur by themselves can be sources of the formation of argon isotopes. Evidently, one should consider reactions of iron nuclei with secondary particles, whose yield for light nuclei increases. The ratio He^3/A^{38} in sample V did not change relative to the other samples, which indicates the common origin of the cosmogenic isotopes of helium and argon in sample V.

Table 2

Sample Nos.*	P, %	S, %	Fe, %	Ni, %	Co, %
13/14	0,26	0,29	93,74	5,91	–
II	0,29	0,005	94,02	6,01	–
III	0,25	0,01	93,84	6,12	0,48
V	7,45	2,35	79,48	11,12	0,33

* The numbering of the samples corresponds to the numbering in Table 1.

There are no direct indications of an assumed increase, in the case of light nuclei, in the yield of secondary particles capable of producing nuclear spallation. Rather, on the contrary, the multiplicity of shower particles increases on passing to nuclei of higher atomic weight. Comparison of the data of Tables 1 and 2 does not reveal a direct quantitative relation between the content of light nuclei and the content of cosmogenic isotopes. Further investigations are needed for a complete explanation of the indicated phenomenon.

In conclusion it should be stated that the experimental data presented cast doubt on the conclusions of works ([3], [17]) concerning depth effects found for some meteorites.

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Note: Figure translations are in progress. See original paper for figures.

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