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COSMIC-RAY-PRODUCED XENON IN METEORITES*

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We have found that xenon extracted from a series of achondritic (stone) meteorites is heavily enriched in Xe^{124}, Xe^{126}, and Xe^{128}. The experimental data reported here seem to lend strong support to the view that the excess amounts of these light isotopes of xenon are cosmic-ray produced.

Considerable attention has been given to the isotopic composition of xenon from meteorites since Reynolds[1,2] reported in these Letters his discovery that the isotopic composition of xenon from both the Richardton and Murray chondrites differed from the atmosphere. Anomalies, with the atmosphere as the standard, were found at virtually every isotope of xenon. Xenon is unique among the elements in exhibiting an effect of this kind and magnitude.

Although many papers have been published on this subject during the past few years, none of the theories proposed seemed to explain various features of the meteoritic xenon anomalies in a satisfactory manner. This has been especially true for the light isotopes of xenon. Previously, large anomalies had been observed only once at Xe^{124}, Xe^{126}, and Xe^{128}. Quite large anomalies in this region were observed in chondrules from the Bruderheim chondrite by Merrihue.[3] No real support was given to any of the mechanisms for production of the anomalies in the light xenon isotopes.

It should be mentioned that the normalization to xenon from the Murray carbonaceous chondrite is of significance. Using this normalization procedure, it is possible to attribute the observed meteoritic anomalies to cosmic-ray spallation reactions. The difference in these light xenon isotopic ratios between the meteorites and the atmosphere is not explained here, although an explanation of this difference has been proposed by Cameron[4] who also normalized to xenon from Murray. The two mechanisms, one to explain the excess of Xe^{124}, Xe^{126}, and Xe^{128} in meteorites over Murray xenon and the other to explain the apparent deficiency in the atmosphere relative to Murray, are independent.

The Reynolds-type mass spectrometer used in this work enables us to measure 10^{-12} to 10^{-13} cc STP per gram of excess xenon isotopes in meteorites with reasonable accuracy. The experimental results are shown in Table I and are also plotted in Fig. 1 against the cosmic-ray exposure ages of the meteorites. In calculating the excess amounts of xenon isotopes, the shielded nuclide Xe^{130} was used as a reference standard for the reasons discussed previously by one of the authors,[5] and we define

$$\Delta_i = \left(\frac{Xe^i}{Xe^{130}}\right)_{\text{sample}} - \left(\frac{Xe^i}{Xe^{130}}\right)_{\text{Murray}}$$

A correction on Xe^{130} was necessary to account for spallation-produced Xe^{130}. This caused

Table I. The concentrations of excess xenon isotopes in some meteorites (all gas contents are in units of 10^{-13} cc STP/g).

Meteorites	Cosmic-ray exposure ages (10^6 years)	Xe^{124}	Xe^{126}	Xe^{128}
Stannern	$13.7^{a,b}$	12	21	22
Pasamonte	2.2^{a}	1.5	2.2	2.2
Juvinas	$5.7^{a,b}$	7.6	12	16
Petersburg	13.2^{c}	16	25	28
Moore County	6^{c}	4.2	7.3	7.3
Pena Blanca Spring	46^{d}	1.3	2.8	1.2

[a] H. Hintenberger, H. König, L. Schultz, and H. Wänke, Z. Naturforsch. 19a, 327 (1964).

[b] T. Kirsten, D. Krankowsky, and J. Zahringer, Geochim. Cosmochim. Acta 27, 13 (1963); and E. Anders, Space Sci. Rev. 3, 583 (1964).

[c] Calculated by the Ne^{21} content measured at our laboratory and the production rate in E. Anders, Space Sci. Rev. 3, 583 (1964).

[d] P. Eberhardt, O. Eugster, and J. Geiss, J. Geophys. Res. 70, 4427 (1965).

only a small change in the values shown in Table I. The same conclusion was drawn before the small corrections were applied.

It has to be pointed out at once that the data for the Pena Blanca Spring meteorite do not appear in Fig. 1. The cosmic-ray exposure age of this meteorite is far greater than the rest of the meteorites studied and yet the amounts of excess Xe^{124}, Xe^{126}, and Xe^{128} are very small. If one excludes this sample, there seems to be a straight-line relationship between the amounts of excess xenon isotopes and the cosmic-ray exposure ages of the meteorites.

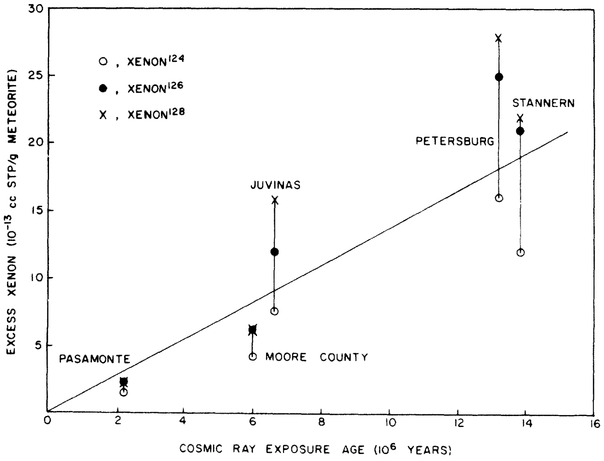

FIG. 1. The amounts of excess Xe^{124}, Xe^{126}, and Xe^{128} plotted against the cosmic-ray exposure age. The straight-line relationship observed is evidence for the mechanism of cosmic-ray spallation reactions on barium.

The fact that the Pena Blanca Spring meteorite seems to contain abnormally low quantities of cosmic-ray-produced xenon isotopes as compared with other meteorites can probably best be explained as due to the low barium content of this meteorite. The Pena Blanca Spring meteorite belongs to the group of enstatite achondrites, whereas the other five meteorites belong to another group, the eucrites. Although barium has not been measured in most of the meteorites studied here, it seems that the barium content of an enstatite achondrite, such as Pena Blanca Spring, is generally much lower than that of the eucrites.

Barium is probably by far the most favorable target for the cosmic-ray production of the light isotopes of xenon by spallation reactions. The quantities of excess xenon isotopes in meteorites then should be directly proportional to both the cosmic-ray exposure age and the barium content of the meteorite. Based on these assumptions, we shall now attempt to calculate the "effective production cross sections" for the light isotopes of xenon from barium.

Barium has been measured in some achondrites and in particular has been measured in two of the meteorites reported here. There are also measurements on meteorites from the same classes as those represented here, and the evidence (while admittedly insufficient) seems to indicate that the abundance of barium is rather constant in a particular achondrite group. The measurements of the barium concentration in three eucrites show Nuevo Laredo,[6] 46 ppm; Stannern,[7] 48 ppm; and Juvinas,[7] 10-30 ppm. Furthermore, confidence in the assignment of barium contents is strengthened by an examination of the strontium measurements. Strontium has been measured in the eucrites Moore County,[8] Nuevo Laredo,[8] Pasamonte,[8,9] and Sioux County,[8] and is fairly constant, varying from 68.8 ppm to 94.7 ppm. Based on this information, we assume that the barium content of all eucrites is 46 ppm. For the enstatite achondrites, the barium content has been measured in Norton County[10] (2 ppm) and Cumberland Falls[10] (14 ppm). It has also been measured in two other calcium-poor achondrites, Johnstown[10] (2.5 ppm) and Shalka[10] (4 ppm). Only one strontium determination could be found for the calcium-poor achondrites.

Table II. Effective cross section for production of Xe^{124}, Xe^{126}, and Xe^{128} from spallation of barium by cosmic rays. A cosmic-ray flux of 5 particles per cm^2 per second was assumed in the meteorite.

Meteorite	Effective production cross section (in units of 10^{-24} cm^2) Xe^{124}	 Xe^{126}	 Xe^{128}
Stannern	0.071	0.124	0.130
Pasamonte	0.058	0.085	0.085
Juvinas	0.097	0.154	0.206
Petersburg	0.102	0.159	0.179
Moore County	0.059	0.103	0.103
Pena Blanca Spring	0.055	0.118	0.051
Average	0.07 ± 0.02	0.12 ± 0.03	0.13 ± 0.06

This one value, 3 ppm[11] for Johnstown, confirms our expectation of a low barium content. We have rather arbitrarily selected a Ba value of 2 ppm to be used for Pena Blanca Spring.

Table II shows the results of these calculations of the "effective production cross sections." Considering the fact that we have chosen meteorites with a wide range of cosmic-ray exposure [(2.2 to 46) × 10^6 yr], a wide range of barium concentrations (2 to 48 ppm), and a varying amount of "primordial" xenon [(0.25 to 1.7) × 10^{-11} cc STP/g], the relatively small variation from the average value of the effective cross sections (0.07 ± 0.02, 0.12 ± 0.03, and 0.13 ± 0.06 barns for Xe^{124}, Xe^{126}, and Xe^{128}, respectively) thus obtained seems to us to be rather firm evidence for the mechanism of cosmic-ray spallation reactions on barium in meteorites during the past few (2 to 50) million years.

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[1] J. H. Reynolds, Phys. Rev. Letters 4, 8 (1960).

[2] J. H. Reynolds, Phys. Rev. Letters 4, 351 (1960).

[3] M. Merrihue, J. Geophys. Res. 68, 352 (1963).

[4] A. G. W. Cameron, in The Origin and Evolution of Atmospheres and Oceans, edited by P. J. Brancazio and A. G. W. Cameron (John Wiley & Sons, Inc., New York, 1964), Chap. 10.

[5] P. K. Kuroda, Nature 187, 36 (1960).

[6] H. Hamaguchi, G. W. Reed, and A. Turkevich, Geochim. Cosmochim. Acta 12, 337 (1957).

[7] D. Von Englehardt, Chem. Erde 10, 187 (1936).

[8] P. W. Gast, J. Geophys. Res. 65, 1287 (1960) and Geochim. Cosmochim. Acta 26, 927 (1962).

[9] E. Schumacher, Z. Naturforsch. 11a, 206 (1956).

[10] C. B. Moore and H. Brown, J. Geophys. Res. 68, 4893 (1963).

[11] W. H. Pinson, L. H. Ahrens, and M. L. Franck, Geochim. Cosmochim. Acta 4, 251 (1953).

BREAKDOWN MINIMA DUE TO ELECTRON-IMPACT IONIZATION IN SUPER-HIGH-PRESSURE GASES IRRADIATED BY A FOCUSED GIANT-PULSE LASER*

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Minima in the curves of threshold electric field versus pressure for ionization of super-high-pressure helium, argon, and nitrogen using a focused giant-pulse ruby laser are reported here. These minima are characteristic of electron impact ionization. Gold and Bebb[1] and others have analyzed ionization produced by focused lasers in terms of multiphoton absorption alone. Tomlinson[2] has shown that while multiphoton absorption may be the trigger mechanism, it cannot explain the subsequent growth of the ionization. Meyerand and Haught[3] have suggested that the mechanism is inverse bremsstrahlung. Askaryan and Rabinovich[4] have commented on the prospective role of electron impact ionization. This Letter presents definitive experimental data which are indicative of electron impact ionization where the heating of electrons occurs through energy transfer from the light wave to the electrons undergoing collisions with neutrals.