A Comparison of the Noble Gases in Three Meteorite Specimens Labeled Springfield

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The abundance and isotopic composition of the noble gases were measured in three Springfield specimens identified by the Denver Museum of Natural History with numbers 7029, 379.13 and 6040. The latter specimen contains more cosmogenic noble gas isotopes than the other two specimens and the abundance pattern of trapped noble gases in specimen 6040 is distinct from that in the other two specimens. Specimen 7029 contains about seven times as much radiogenic ^{40}Ar and about four times as much radiogenic ^{129}Xe as does specimen 379.13. These results indicate that the three specimens did not come from a single meteoroid.

The chemical inertness and volatility of the noble gases caused them to be highly depleted from more condensable material when planetary solids were formed in the solar system. As a result of this separation, these gases hold important clues of many nuclear and physical processes which have occurred in planetary solids. Bogard [1] gives a review of the numerous investigations undertaken to decipher the noble gas record of lunar and meteoritic samples.

In addition to providing a record of nuclear processes, the noble gases have been altered by fractionation processes. In 1949, Suess [2] and Brown [3] independently noted that the Earth's inventory of noble gases, when compared with the solar abundance of these elements, showed a preferential loss from terrestrial material of the gases lighter than krypton. The trapped noble gases in stone meteorites display a similar fractionation pattern [4, 5], except that the fractionation extends to xenon. In typical chondrites the Kr : Xe, Ar : Xe and Ne : Xe ratios are $\approx 10^{-1}$, $\approx 10^{-3}$ and $\approx 10^{-4} - 10^{-5}$, respectively, of solar values.

This study of the abundance pattern and isotopic composition of noble gases in the Springfield stone meteorite, which Hey [6] classifies as a crystalline spherical olivine-hypersthene chondrite, was undertaken to see if there were differences in the noble gas records of three specimens identified by the Denver Museum of Natural History with numbers 7029, 379.13 and 6040.

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Measurements

The samples of Springfield were furnished to us for a cooperative study by Mr. Jack Murphy of the Denver Museum of Natural History. The name, number and weight of each sample used in this study are as follows: first analyses: Springfield meteorite 7029, 1.065 g; Springfield meteorite 379.13, 1.309 g; Springfield meteorite 6040, 0.5710 g. Second analyses: Springfield meteorite 7029, 0.543 g; Springfield meteorite 379.13, 0.795 g.

The samples were mounted in side-arm chambers of a water-cooled quartz extraction bottle and the pressure reduced to $\approx 10^{-8}$ torr. Following blank and calibration analyses, the sample was dropped into a previously degassed molybdenum crucible, where the extraction of noble gases was accomplished by heating with radio-induction. The procedures used for cleaning and separating noble gases are described in an earlier paper [7].

In the first series of analyses, the samples were not heated in the vacuum system prior to dropping into the molybdenum crucible for gas extraction. A single extraction temperature, ≈ 1700 °C, was employed to melt the sample and release noble gases for analysis. In the second series of analyses the samples were preheated overnight at ≈ 150 °C to remove surface adsorbed gases, and the gases were extracted by stepwise heating. Gases released at a low extraction temperature (≈ 800 °C) were collected, cleaned and analyzed, and then the sample was melted by heating to ≈ 1700 °C to release gases for the high temperature fraction. The second series of analyses was limited to samples 7029 and 379.13 due to a limited supply of sample 6040.

The gases were analyzed statically in a Reynold's type 4.5 inch 60° sector mass spectrometer [8]. The mass spectrometer was calibrated before and after

each sample by analyzing standard volumes of air (≈ 0.01 cc STP) by the same procedure of analysis as used for the sample. The sensitivity of the mass spectrometer for each noble gas and the mass discrimination across the isotopes of each gas were calculated by comparing the mass spectrometer signal for the air standards with abundances [9] and isotopic compositions of neon [10], argon [11], krypton [12], and xenon [13] in air. No correction for mass discrimination was applied to helium.

Results and Discussion

The results of the two series of analyses are presented in Table I and Table II. Errors shown on the isotopic ratios represent one standard deviation (σ) from a least squares line through the observed ratios, plotted as a function of residence time in the mass spectrometer. Due to variations in the sensitivity of the mass spectrometer the gas content of each noble gas has an estimated error of $\pm 20\%$. Mass spectrometer signals from blank analyses, where identical procedures were followed in analyzing gases evolved by heating the empty molybdenum crucible to the highest temperature to be used for extraction of gases from the sample, have been converted to effective gas concentrations and are shown in Table I and Table II for the reference isotope of each noble gas. The isotopic composition of the blanks were atmospheric. Since there is no way to assure complete removal of atmospheric noble gases adsorbed on meteorite surface, atmospheric contamination may be responsible for an appreciable fraction of the heavier noble gases, particularly in the case of Xe, in the first series of analyses.

1. Cosmo- and Radio-genic Isotopes

Major alterations in the isotopic composition of noble gases in the three Springfield specimens have occurred from spallation reactions induced by cosmic rays and from the spontaneous decay of ^{40}K, ^{129}I, ^{235}U, ^{238}U, and ^{232}Th. The concentrations of cosmogenic and radiogenic noble gas isotopes in the three Springfield specimens are shown in Table III. In calculating the values shown there, we assumed

Table I. Results of first series of analyses.

Noble gas	Sample 7029	Sample 6040	Sample 379.13
Isotope ratios			
$^4He/^3He$	149.2 ± 0.8	18.4 ± 0.1	42.2 ± 0.2
$^{20}Ne/^{22}Ne$	1.57 ± 0.01	1.06 ± 0.02	1.24 ± 0.03
$^{21}Ne/^{22}Ne$	0.754 ± 0.002	0.899 ± 0.003	0.812 ± 0.03
$^{38}Ar/^{36}Ar$	0.312 ± 0.002	0.740 ± 0.009	0.345 ± 0.001
$^{40}Ar/^{36}Ar$	3085 ± 20	1217 ± 4	283.9 ± 1.0
$^{80}Kr/^{84}Kr$	0.0457 ± 0.0007	—	0.0435 ± 0.0004
$^{82}Kr/^{84}Kr$	0.208 ± 0.001	—	0.208 ± 0.002
$^{83}Kr/^{84}Kr$	0.206 ± 0.001	—	0.206 ± 0.001
$^{86}Kr/^{84}Kr$	0.309 ± 0.002	—	0.308 ± 0.001
$^{124}Xe/^{130}Xe$	0.0241 ± 0.002	—	0.0242 ± 0.0004
$^{126}Xe/^{130}Xe$	—	—	—
$^{128}Xe/^{130}Xe$	0.475 ± 0.004	—	0.469 ± 0.002
$^{129}Xe/^{130}Xe$	6.74 ± 0.02	6.46 ± 0.02	6.58 ± 0.02
$^{131}Xe/^{130}Xe$	5.14 ± 0.03	5.13 ± 0.04	5.15 ± 0.03
$^{132}Xe/^{130}Xe$	6.53 ± 0.03	6.49 ± 0.06	6.55 ± 0.03
$^{134}Xe/^{130}Xe$	2.56 ± 0.02	2.50 ± 0.02	2.54 ± 0.01
$^{136}Xe/^{130}Xe$	2.17 ± 0.02	2.14 ± 0.01	2.14 ± 0.01
Gas content (cc STP/g)			
^4He (sample)	9.89×10^{-6}	7.97×10^{-6}	1.13×10^{-6}
^4He (blank)	0.04×10^{-6}	0.08×10^{-6}	0.03×10^{-6}
^{22}Ne (sample)	1.47×10^{-8}	8.27×10^{-8}	9.23×10^{-9}
^{22}Ne (blank)	0.01×10^{-8}	0.02×10^{-8}	0.14×10^{-9}
^{36}Ar (sample)	1.76×10^{-8}	2.48×10^{-8}	2.50×10^{-8}
^{36}Ar (blank)	0.01×10^{-8}	0.03×10^{-8}	0.01×10^{-8}
^{84}Kr (sample)	9.12×10^{-11}	5.41×10^{-11}	6.79×10^{-11}
^{84}Kr (blank)	0.05×10^{-11}	0.03×10^{-11}	0.08×10^{-11}
^{130}Xe (sample)	3.75×10^{-11}	1.99×10^{-11}	3.92×10^{-11}
^{130}Xe (blank)	0.01×10^{-11}	0.02×10^{-11}	0.01×10^{-11}

Table II. Results of second series of analyses.

	Sample 379.13 ≈ 750 °C	Sample 379.13 ≈ 1700 °C	Sample 7029 ≈ 900 °C	Sample 7029 ≈ 1700 °C
Isotope ratios				
$^{4}He/^{3}He$	242.2 ± 1.0	53.7 ± 0.2	169.4 ± 0.4	154.1 ± 0.4
$^{20}Ne/^{22}Ne$	—	1.24 ± 0.01	—	1.56 ± 0.01
$^{21}Ne/^{22}Ne$	—	0.810 ± 0.002	—	0.759 ± 0.003
$^{38}Ar/^{36}Ar$	0.196 ± 0.001	0.342 ± 0.001	0.232 ± 0.003	0.307 ± 0.002
$^{40}Ar/^{36}Ar$	306.9 ± 1.4	315.7 ± 1.0	2891 ± 30	2144 ± 35
$^{124}Xe/^{130}Xe$	—	0.0261 ± 0.0004	—	0.0279 ± 0.0002
$^{126}Xe/^{130}Xe$	—	0.0244 ± 0.0003	—	0.0259 ± 0.0002
$^{128}Xe/^{130}Xe$	—	0.488 ± 0.003	0.499 ± 0.02	0.510 ± 0.003
$^{129}Xe/^{130}Xe$	6.48 ± 0.04	7.04 ± 0.03	6.57 ± 0.04	8.16 ± 0.04
$^{131}Xe/^{130}Xe$	5.15 ± 0.02	5.16 ± 0.02	5.10 ± 0.04	5.09 ± 0.02
$^{132}Xe/^{130}Xe$	6.55 ± 0.04	6.46 ± 0.04	6.45 ± 0.02	6.25 ± 0.03
$^{134}Xe/^{130}Xe$	2.53 ± 0.02	2.47 ± 0.01	2.49 ± 0.02	2.38 ± 0.01
$^{136}Xe/^{130}Xe$	2.15 ± 0.02	2.09 ± 0.01	2.12 ± 0.01	1.99 ± 0.01
Gas content (cc STP/g)				
^{4}He (sample)	4.32×10^{-7}	9.59×10^{-7}	3.29×10^{-6}	4.75×10^{-6}
^{4}He (blank)	—	0.35×10^{-7}	—	0.05×10^{-6}
^{22}Ne (sample)	—	1.04×10^{-8}	—	1.91×10^{-8}
^{22}Ne (blank)	—	0.02×10^{-8}	—	0.04×10^{-8}
^{36}Ar (sample)	2.00×10^{-9}	2.22×10^{-8}	5.51×10^{-9}	1.73×10^{-8}
^{36}Ar (blank)	—	0.03×10^{-8}	—	0.06×10^{-8}
^{84}Kr (sample)	3.79×10^{-11}	7.19×10^{-11}	4.52×10^{-11}	8.54×10^{-11}
^{84}Kr (blank)	—	0.03×10^{-11}	—	0.04×10^{-11}
^{130}Xe (sample)	1.60×10^{-12}	1.41×10^{-11}	3.19×10^{-12}	2.16×10^{-11}
^{130}Xe (blank)	—	0.01×10^{-11}	—	0.01×10^{-11}

that ^{21}Ne and ^{3}He are entirely cosmogenic and that ^{40}Ar is entirely radiogenic. Since there is no reliable method to distinguish between radiogenic ^{4}He and trapped ^{4}He, concentrations of the former are not listed in Table III. The concentrations of cosmogenic ^{38}Ar were calculated by assuming that trapped argon contains ^{36}Ar and ^{38}Ar in the proportions found in air, i. e., $^{36}Ar:{}^{38}Ar = 5.35$ (Ref. [11]), and cosmogenic argon contains $^{36}Ar:{}^{38}Ar = 0.66$ (Ref. [14]). Due to the small concentrations of krypton in these samples, reliable isotopic analyses were only possible in the two larger samples, specimens 7029 and 379.13 of the first series of analyses. The krypton spectra in these two specimens can be accounted for by a mixture of the trapped krypton observed in average carbonaceous chondrites [15, 16] with krypton isotopes produced by exposure to cosmic rays, i. e., those produced from spallation-induced reactions on heavier nuclei and neutron-capture reactions on bromine [17]. However, the isotopic anomalies of krypton are too small to be of value in identifying differences in the exposure history of these two Springfield specimens. The concentrations of radiogenic ^{129}Xe given in Table III were calculated by assuming a trapped xenon component with $^{129}Xe/^{130}Xe = 6.48$.

2. Abundance Patterns of Trapped Noble Gases

Before discussing differences in the noble gas record of nuclear processes in the three Springfield specimens, as summarized in Table III, let us briefly

Table III. Concentrations of cosmogenic and radiogenic noble gases in Springfield specimens (10^{-8} cc STP/g).

Specimen No.	Analysis No.	Wt. (g)	Cosmogenic			Radiogenic	
			^{3}He	^{21}Ne	^{38}Ar	^{40}Ar	^{129}Xe
7029	1	1.065	6.63	1.11	0.251	5430	0.00098
7029	2	0.543	5.02	1.45	0.265	5302	0.00366
379.13	1	1.309	2.68	0.75	0.451	710	0.00039
379.13	2	0.795	1.96	0.84	0.395	762	0.00079
6040	1	0.571	43.3	7.43	1.56	3018	0.00000

examine the abundance patterns of trapped noble gases. For this purpose we compute values of the fractionation factor, F^m, for a nonradiogenic isotope of each noble gas using the equation of Canalas et al.[18],

$$F^m = (^mX/^{130}Xe)_{\text{meteorite}}/(^mX/^{130}Xe)_{\text{cosmic}}. \quad (1)$$

In Eq. (1) X^m is any trapped noble gas isotope of mass number, m, and cosmic abundances of elements[19] are used to calculate the ratio in the denominator. The fractionation patterns for noble gases in the three Springfield specimens are shown in Fig. 1 in a plot of log F^m vs m.

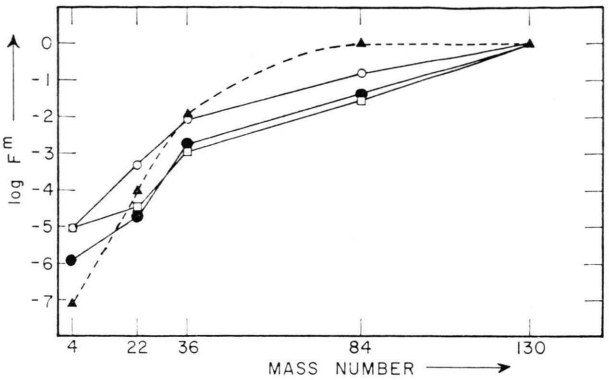

Fig. 1. A comparison of the abundance patterns of trapped noble gases in the three Springfield specimens. Fractionation factors, F^m, are defined by Equation (1). The dashed line shows the fractionation pattern of noble gases in air and the solid lines show the fractionation pattern of noble gases in each specimen. ● Specimen 379.2; □ Specimen 7029; and ○ Specimen 6040.

3. Comparison of Noble Gas Records in Springfield Specimens

The following is worthy of note in comparing the noble gas records summarized in Table III and in Figure 1.

i) The fractionation pattern of noble gases in specimen 6040, as shown in Fig. 1, is distinct from that in the other two specimens. The trapped noble gases in 6040 show less selective depletion of the lighter weight noble gases than do the noble gases in 379.13 and 7029.

ii) From the amounts of spallation-produced ^3He, ^{21}Ne, and ^{38}Ar shown in Table III, it is clear that specimen 6040 has had more exposure to cosmic rays than the other two Springfield specimens.

iii) In specimens 6040 and 7029 the ratios of cosmogenic neon and argon are similar, $^{38}Ar:^{21}Ne \approx 0.21$, suggesting similar relative abundances of target nuclides in these two specimens. Specimen 379.13 shows a distinctively different relative production rate for cosmogenic noble gases with $^{38}Ar:^{21}Ne \approx 0.5$.

iv) Specimen 379.13 clearly shows a lower content of radiogenic ^{40}Ar than do the other two specimens. Specimen 7029 has the highest concentration of both radiogenic ^{40}Ar and radiogenic ^{129}Xe. No radiogenic ^{129}Xe was observed in specimen 6040.

From the above comparisons we conclude that these three specimens were separate entities in space and thus represent separate meteorites.

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