14149, suggesting local provenance (7). If this exotic component is transported over long distances on the moon and mixed with the soils, it should preferentially occur in the smaller size ranges of the soils from the Apollo 11 and Apollo 12 missions.

The abundances of K, Rb, Sr, and Ba in sample 15555 resemble, but are slightly lower, than those in the low-K mare basalts from the Sea of Tranquillity. Striking similarities are apparent between this sample and the basalts returned from the Ocean of Storms (*2, 5*), not only in age and initial Sr content, as mentioned earlier, but also in elemental abundances anl elemental ratios (*2*). The elemental abundances of K, Rb, Sr, and Ba are quite low, however, relative to those of the Apollo 14 basalts. The range in elemental abundances observed in the basaltic rock samples thus far returned from the moon could result from differences in the composition of the source region, differentiation processes, degree of contamination with previously differentiated material, or a combination of these. It is clear, however, that simple fractionation alone from a homogeneous source is not adequate to explain the data. If a homogeneous source exists, fractionation in combination with contamination must be invoked.

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Rare Gas Record in the Largest Apollo 15 Rock

Abstract. *The spallation krypton data from rock chip 15555,23 indicate a well-shielded location during most of the time during which the rock was exposed to cosmic rays. A krypton-krypton exposure age of* $81^{+17}_{-7} \times 10^6$ *years is calculated, and the gas retention ages are estimated. No evidence for the presence of products from plutonium-244 or iodine-129 was found.*

Results obtained from rare gas isotopic abundances in a large lunar rock may provide us with data on the depth dependence of cosmic-ray induced spallation yields, as well as information about ages and irradiation history, whenever the rock had a simple one-stage irradiation history. This information is required for an understanding of lunar surface processes and turnover rates. Estimates of the depth of the lunar regolith are crucially dependent on the spallation and neutron record in the soil and core samples. We have analyzed by mass spectrometry the noble gases He, Ne, Ar, Kr, and Xe in a 182-mg chip of rock 15555. This is a chip from a fragment that broke off in transit and whose orientation relative to the rock and to the lunar surface is unfortunately not known.

Microscopic inspection has shown that fine dust was adhering to one side of the chip. Since we were mainly interested in the spallation gas record, we attempted to remove dust and surface material containing solar wind components by a short HF etching and ultrasonic cleaning. The analytical techniques used have been reported (*1*). A technique of stepping the magnetic field was employed. The errors given include, in general, errors from all sources, quadratically added. Errors in Kr and Xe data reflect both the limited sample size available for this study and the relatively low abundances of the major target elements Sr, Y, Zr, Ba, and the rare earth elements (REE). The ^{81}Kr content in our sample was only 0.012×10^{-12} cm^3 at standard temperature and pressure (STP). The ^{81}Kr and ^{78}Kr mass peaks were resolved from the interfering isobaric hydrocarbon background.

The relatively small $^{131}Xe/^{126}Xe$ spallation ratio (Table 1) might indicate a fairly hard irradiation, and, therefore, a close-to-surface irradiation of the analyzed chip. A closer inspection of the data, however, revealed that this was not the case. The relative spallation Kr yields (Table 2) are compatible only with a shielded location. In the diagram of P_{81}/P_{83} versus $^{78}Kr/^{83}Kr$ (Fig. 1), the data point for rock 15555 falls on or close to the correlation line of the Apollo 12 rocks, which indicates similar abundance ratios of the major target elements Zr and Sr for Apollo 12 rocks and rock 15555. The position of this data point in this diagram requires an effective shielding similar to those of rocks 12009 and 12052, corresponding to a model depth of ~ 150 g/cm^2 (*2*). From the preliminary description of the Apollo 15 lunar

Table 1. Concentrations and isotopic compositions of Xe in rock 15555,23. The isotopic composition of Xe in the 800°C fraction of sample 10084,29 (*1*) was used for the trapped component.

Lunar rock	^{131}Xe [$\times 10^{-12}$ cm^3/g (STP)]	^{124}Xe	^{126}Xe	^{128}Xe	^{120}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
15555,23	12.6 ± 1.8	6.37 ± 0.14	11.48 ± 0.27	20.8 ± 0.3	80.2 ± 1.8	18.9 ± 0.5	100	66.2 ± 0.9	23.7 ± 0.4	18.8 ± 0.5
Spallation Xe*	$^{126}Xe = 1.45$	0.546	1.00	1.431	1.81	0.851	4.74	0.763	0.135	≡ 0.028
Spallation Xe†	$^{126}Xe = 1.45$	0.546	1.00	1.423	1.72	0.836	4.66	0.670	0.100	≡ 0

* A spallation ratio for $^{136}Xe/^{131}Xe$ of 0.0059 is assumed, which represents an upper limit for this spallation ratio (*2*). † A spallation ratio for $^{136}Xe/^{131}Xe$ of 0 is used.

Table 2. Concentrations and isotopic composition of Kr in rock 15555,23.

Lunar rock	^{83}Kr [$\times 10^{-12}$ cm^3/g (STP)]	^{78}Kr	^{80}Kr	^{81}Kr	^{82}Kr	^{83}Kr	^{84}Kr	^{86}Kr
15555,23	40 ± 6	12.9 ± 0.3	40.6 ± 0.5	0.169 +0.014 −0.030	79.3 ± 0.7	100	141 ± 6	32.1 ± 1.9
Spallation Kr*	32	15.5 ± 0.4	46.0 ± 0.5	0.212 + 0.017 −0.038	74.0 ± 0.8	100	50 ± 4	≡ 1.50

* A spallation ratio for $^{86}Kr/^{83}Kr$ of 0.015 is assumed (2). The choice of the trapped component is not crucial. Both atmospheric and meteoritic trapped Kr give spallation spectra which agree within experimental errors. The isotopic composition of atmospheric Kr was used here.

Table 3. Concentrations and isotopic compositions of He, Ne, and Ar in rock 15555,23.

^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	$\left(\frac{^{22}Ne}{^{21}Ne}\right)_{spall}$	$\left(\frac{^{38}Ar}{^{36}Ar}\right)$
			[$\times 10^{-8}$ cm^3/g (STP)]						
62.4 ± 1.9	5770 ± 170	10.2 ± 0.4	9.98 ± 0.30	11.73 ± 0.35	5.7 ± 0.3	8.7 ± 0.4	690 ± 35	1.168 ± 0.006	1.519 ± 0.007

samples (3), a Zr/Sr ratio of 0.85 was calculated for rock 15555, which is, in fact, similar to the ratios in Apollo 12 rocks. On the other hand, the $^{131}Xe/^{126}Xe$ spallation ratio in rock 12052 is 7.83, which is in contrast with a ratio of 4.7 in rock 15555. This discrepancy can only be resolved if a different relative abundance of the major target elements for spallation Xe, Ba and REE, is assumed. Thus, the abundance ratio (La + Ce + Nd)/Ba in rock 15555,23 should be larger than that in Apollo 12 rocks. Other spallation Xe yields support this conclusion. The relative yields of ^{130}Xe and ^{132}Xe are considerably smaller in rock 15555 than in Apollo 12 rocks, and resemble those

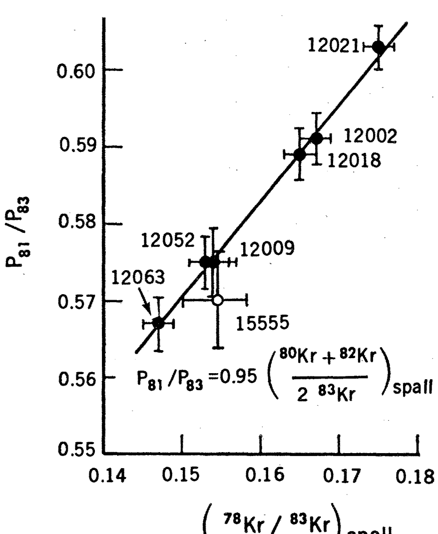

Fig. 1. Correlation of the Kr production ratio P_{81}/P_{83} with $^{78}Kr/^{83}Kr$ for Apollo 12 rocks (2). The data point for rock 15555 is close to that for rocks 12009 and 12052.

found in Apollo 11 B rock 10047 (1). Apollo 11 B rocks, in fact, do have (La + Ce + Nd)/Ba abundance ratios that are larger by a factor of 2. In addition, low ^{130}Xe and ^{132}Xe spallation yields from REE targets were found by Kaiser (4) in his work on rock 12013. However, the small relative yield of ^{132}Xe may in part also be due to an underestimation of fission Xe content. The applied correction for fission Xe is based on a U content of 0.092 part per million and an isochron age of 3.35×10^9 years (5), and does not include a possible neutron-induced ^{235}U fission component. The U content was calculated from the measured K content: 0.025 percent K (3) and an average K/U ratio of 2700 for Apollo 15 crystalline rocks (3).

The time of exposure to cosmic rays obtained by the ^{81}Kr-Kr method (6) is $T_r = 81^{+17}_{-7} \times 10^6$ years. This can be compared to a ^{3}He age of 62×10^6 years, if a ^{3}He production rate of 1.0×10^{-8} cm^3/g (STP) per 10^6 years is used. The ^{21}Ne and ^{38}Ar contents in Table 3, combined with $T_r = 81 \times 10^6$ years, give production rates of 0.12×10^{-8} and 0.11×10^{-8} cm^3/g (STP) per 10^6 years for ^{21}Ne and ^{38}Ar, respectively. The Ne, ^{36}Ar, and ^{38}Ar data indicate that these isotopes represent almost pure spallation products. The Kr and Xe results (Tables 1 and 2), on the other hand, indicate the presence of a sizable trapped component. The nature of the trapped component is at present not completely understood. If it represents solar-type gas, then a strong element fractionation is indicated. The position of rock 15555 in the (P_{81}/P_{83}, $^{78}Kr/^{83}Kr$) correlation (Fig. 1) rules out a significant contribution to ^{80}Kr and ^{82}Kr from neutron capture in Br.

The radiogenic ^{4}He and ^{40}Ar concentrations given in Table 3, if combined with K and U data, allow us to make estimates of the gas retention ages. It should be stressed that these are estimates, since K was not measured in an aliquot of the sample, and the U content is estimated. Nevertheless, the U/Th-He age of 2.3×10^9 years and the K-Ar age of 2.8×10^9 years indicate that some loss of radiogenic gases probably did occur. There is no evidence for the presence of products from extinct ^{129}I or ^{244}Pu.

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