Detection of a Nonuniform Distribution of Polonium-210 on the Moon with the Apollo 16 Alpha Particle Spectrometer

Abstract. *The polonium-210 activity of the lunar surface is significantly larger than the activity of its progenitor radon-222. This result establishes unequivocally that radon emanation from the present-day moon varies considerably within the 21-year half-life of lead-210, the parent nuclide of polonium-210. There are large variations and well-localized enhancements in polonium-210 activity over much of the moon's surface.*

The Apollo alpha particle spectrometer consisting of collimated silicon surface barrier detectors was an orbiting instrument flown on Apollo 15 and Apollo 16. A description of the instrument may be found in the Apollo 15 preliminary science report (*1*). The purpose of the observation was to detect alpha particles from the decay of radon and her daughter products in the uranium and thorium decay chains. The importance of radon in these series is that it is a noble gas and can under certain conditions diffuse to the lunar surface (*2, 3*) so that decay alphas can be detected and mapped from lunar orbit. The mapping of radon gas or her decay products is significant because localized concentrations are found in the data and they are probably indicative of localized internal activity. On the earth radon is a trace component of gas released to the atmosphere. During terrestrial seismic or volcanic events, which result in increased venting of gases, there is a corresponding transient increase in the radon emission. The localized concentrations which appear to correlate with other evidence of lunar internal activity at specific sites will be discussed in more detail in forthcoming papers (*4*).

From Apollo 15 observations we have reported the detection of a local increase in the rate of ^{222}Rn decays from the vicinity of the crater Aristarchus (*5*), which we interpreted as an indication of internal activity at that site. Here we present a preliminary map of the distribution of ^{210}Po across the Apollo 16 ground track and a comparison with overlapping portions of the Apollo 15 ground track. We also present preliminary results for our measurement of ^{222}Rn activity during Apollo 16.

The presence of ^{222}Rn with her prompt daughters ^{218}Po and ^{214}Po indicates very recent release of ^{222}Rn from the lunar regolith. The ratio of the intensities of alpha emission from ^{222}Rn and her prompt daughters is established after about 10 minutes of ^{222}Rn production at a uniform rate. Since the half-life of ^{222}Rn is 3.8 days, any measurable signal from the above three elements is expected to vanish 10 to 15 days after diffusion to the surface has stopped.

Detection of ^{210}Po constitutes an entirely different class of observation because its production is held up by the 21-year half-life of ^{210}Pb. The presence of ^{210}Po along with ^{222}Rn and daughter products implies continuing radon diffusion, whereas detection of ^{210}Po alone indicates diffusion that ceased days to years previously. A nonuniform distribution of ^{210}Po implies localized ^{222}Rn emanation in the recent past. However, a single measurement of ^{210}Po activity is insufficient to determine whether ^{222}Rn emanation has occurred continuously (or sporadically) for about 21 years, or whether there was a single large event of short duration.

Apollo 16 had an orbit of low inclination, so that our ground track was limited to ± 11° from the lunar equator. For comparison, the Apollo 15 ground track covered latitudes to ± 30° from the equator. The Apollo 16 orbit did not give us as extensive coverage of the lunar surface as Apollo 15 but did provide a more intensive, more sensitive observation of the area covered. Areas of overlap between the two flights were longitudes 35°E to 105°E and 65°W to 140°W, with various latitudes between 8°N and 11°S. The total useful observing time during Apollo 16 was approximately 85 hours.

The spatial distribution of the ^{210}Po decay rate observed during this period is shown in Fig. 1. The variation is very striking. In general, there is an increase starting at 90°W (Oceanus Procellarum), continuing across the front side of the moon, and reaching a maximum over Mare Fecunditatis and Mare Smythii. The rate drops dramatically to

Table 1. Rate of ^{210}Po activity across the Apollo 16 ground track. The values are counts per second $\times 10^{-3}$ above an assumed constant background of 21.0×10^{-3} count/sec. The time of observation per longitude bin, in seconds, is given in parentheses. To convert counts per second to equivalent disintegrations per square centimeter per second multiply by 0.36.

Longitude	Latitude			
	15°S–10°S	10°S–0°	0°–10°N	10°N–15°N
0°E–20°E		3.3 ± 1.8 (7654)		
20°E–40°E		5.1 ± 1.8 (7744)		
40°E–60°E		7.5 ± 1.9 (7587)		
60°E–80°E		11.1 ± 2.3 (6222)	14.9 ± 6.8 (781)	
80°E–100°E		11.5 ± 3.9 (2122)	− 3.6 ± 3.0 (1396)	
100°E–120°E		3.3 ± 6.1 (658)	− 2.1 ± 2.6 (2702)	
120°E–140°E			5.1 ± 2.8 (3448)	
140°E–160°E			2.9 ± 2.3 (4470)	− 4.8 ± 4.7 (741)
160°E–180°			0.2 ± 2.0 (5097)	− 6.0 ± 4.3 (798)
180°–160°W			4.3 ± 2.1 (5927)	
160°W–140°W			2.7 ± 2.3 (4511)	
140°W–120°W			0.7 ± 2.2 (4507)	
120°W–100°W		− 1.4 ± 6.2 (511)	1.1 ± 2.6 (3211)	
100°W–80°W		0.1 ± 3.2 (2036)	4.7 ± 3.3 (2375)	
80°W–60°W		5.7 ± 2.2 (5721)	6.0 ± 5.5 (900)	
60°W–40°W		1.6 ± 1.8 (7129)		
40°W–20°W	0.4 ± 3.8 (1449)	7.1 ± 2.2 (5703)		
20°W–0°	1.6 ± 4.1 (1374)	6.7 ± 2.2 (5892)		

Table 2. Polonium-210 activity of the lunar surface.

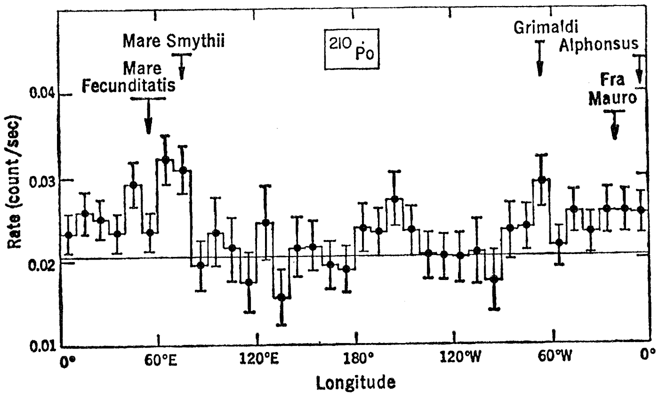
Location	Method	Result (dis cm^{-2} sec^{-1})	Ref.
Average	Theoretical, terrestrial model	2	(*2*)
Mare Tranquillitatis	Surveyor 5, in situ	0.042 ± 0.014	(*6*)
Sinus Medii **Tycho**	Surveyor 6, in situ Surveyor 7, in situ	< 0.021	(*6*)
Oceanus Procellarum	Returned Surveyor 3 visor	$< 1.3 \times 10^{-2}$ (3-S.D. limit)	(*7*)
Mare Tranquillitatis	Returned lunar soil and rock	$< 4.5 \times 10^{-4}$	(*8*)
Oceanus Procellarum	Returned solar wind composition foil	$(2.4 \pm 0.4) \times 10^{-2}$	(*9*)
Apollo 15–Apollo 16 ground track	Orbiting alpha spectrometer	Avg. = $(1.5 \pm 0.4) \times 10^{-3}$ Peak = $(4.0 \pm 0.8) \times 10^{-3}$	

the east of Mare Smythii and remains low throughout the lunar farside. A local increase (60°W to 70°W) occurs in the vicinity of the crater Grimaldi or the southwest edge of Oceanus Procellarum, or both.

The other evidence that we are detecting lunar ^{210}Po is given in Fig. 2. We compare spectra recorded in our instrument over two large regions of the moon, the first from 40°E to 80°E representing a region of high activity, and the second from 110°E to 170°E representing a region of lower activity. The total observation times involved are 14.3×10^3 and 12.9×10^3 seconds, respectively. Two curves are shown in Fig. 2a, normalized to equal observation times. Figure 2b shows the difference between the two curves and clearly indicates the presence of excess ^{210}Po in the region 40°E to 80°E, in the energy channels where it is expected. The difference is essentially zero in the energy channels which contain background, as would be expected for a spatially independent component. (To the left of channel 28, the differences are larger but are not statistically significant because of the greatly increased count rate at the position of the calibration source.) The excess rate of ^{210}Po is 0.0085 ± 0.0015 count/sec in our detector, corresponding to a lunar rate of $(3.1 \pm 0.5) \times 10^{-3}$ disintegrations (dis) per square centimeter per second when our effective area and field are taken into account. During Apollo 15 we observed a rate of $(4.6 \pm 1.3) \times 10^{-3}$ dis cm^{-2} sec^{-1} from the same region of the moon, which is consistent with our present result.

The spectrum of Fig. 2 also indicates the presence of ^{222}Rn, at a confidence level of about 3 standard deviations (S.D.). It is clear that the difference in activity of ^{210}Po between the two regions is much greater than that of ^{222}Rn. Thus, we have positive evidence that the greater activity of the region 40°E to 80°E compared to the region 110°E to 170°E is a result of radon emanation varying in time. We are presently examining the data for evidence of finer structure in the spatial variation at energies corresponding to ^{222}Rn (plus ^{218}Po and ^{214}Po) and ^{210}Po (*4*).

Table 1 shows the measured rate of ^{210}Po activity across the Apollo 16 ground track as a function of both latitude and longitude. The rates given are above an assumed constant background. The background rate was obtained from about 2 hours of observation with a closed cover between the detector and the lunar surface. The closed cover data are consistent with the assumption that the regions of the moon showing the lowest count rate have ^{210}Po activity below the sensitivity of our instrument. The 1-S.D. upper limit to activity in



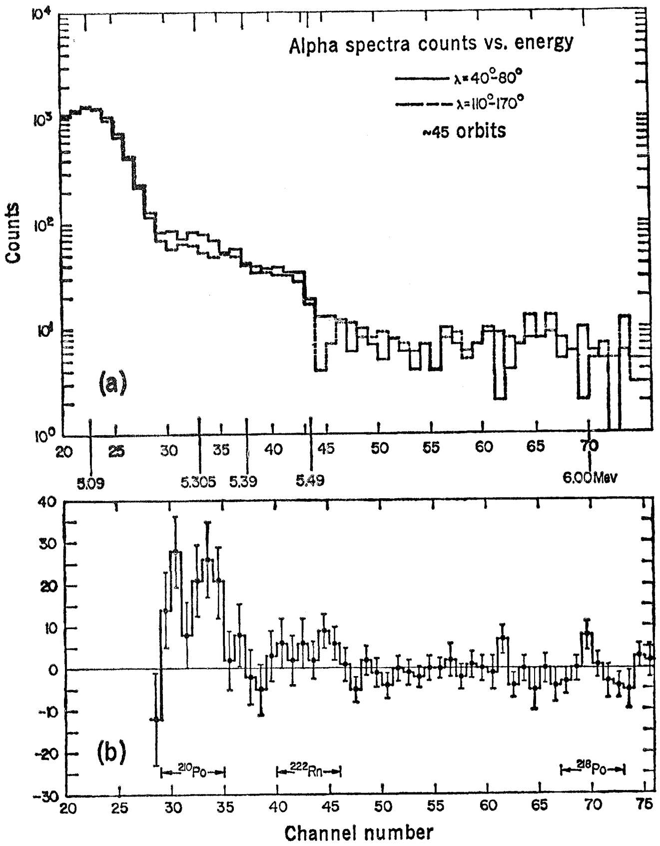


Fig. 1 (left). Measured count rate across the Apollo 16 ground track at energy corresponding to lunar ^{210}Po. The straight line is the background observed during lunar orbit with a cover over the detectors. The field of view of the instrument on the lunar surface is a circle with a 3.7° diameter (full width at half-maximum) as measured on a great circle. Error bars, 1 S.D. Fig. 2 (right). (a) Comparison of spectra from lunar longitudes 40°E to 80°E (solid line) and 110°E to 170°E (dashed line). The channel numbers are linearly related to energy; the energies of the decay alphas and calibration source alphas are indicated. (b) Difference between the two regions, showing excess ^{210}Po and ^{222}Rn in the region 40°E to 80°E. The difference in the energy range where background predominates vanishes as expected. Error bars, 1 S.D.

these regions, under this assumption, is 2×10^{-3} count/sec, or 7×10^{-4} dis cm^{-2} sec^{-1}. An error in background determination would change all of the rates equally, leaving the differences unchanged.

The Apollo 16 data alone seem to indicate that ^{210}Po is found principally on the near side of the moon, with less on the far side. However, Apollo 15 data show a uniformly high rate from north of Mare Tranquillitatis, southeastward to the Van de Graaff region on the far side. In the regions of overlap, which are near the equator, the two observations agree.

Our global observations of ^{210}Po on the lunar surface provide the context for previous measurements. Table 2 is a list of the results of previous attempts to measure the ^{210}Po concentration on the lunar surface. The techniques used were both in situ measurements and terrestrial analysis of returned samples. There is a large spread among the measurements. Before our measurements it was very difficult to reconcile these widely divergent data points. They could not be explained by variation in the concentration of uranium, the source of ^{222}Rn. Our data taken from orbit over a large region of the moon indicate that there are large point-to-point variations in ^{210}Po concentration. Thus, it is not surprising that measurements made at different places and at different times do not agree.

Also, since the rate of ^{210}Po decay observed is in all cases far in excess of the expected equilibrium rate with ^{222}Rn, the emanation and diffusion of radon vary greatly in time. We previously reported a localized increase in ^{222}Rn activity in the vicinity of the crater Aristarchus, which we interpreted as an indication of internal activity (*1*). The spatial and temporal variation reported here gives further support to the idea that internal processes influence radon emanation on the lunar surface.

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10. We thank H. Gursky for discussions on this report. Supported by NASA contract NAS9-9982.

12 February 1973

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A Low-Temperature Thermal Process for the Decomposition of Water

Abstract. *The following three reactions, each of which has been shown to proceed at the temperature indicated above the arrow, are suggested as a cycle for the thermal decomposition of water:*

$$LiNO_2 + I_2 + H_2O \xrightarrow{300°K} LiNO_3 + 2HI$$

$$2HI \xrightarrow{700°K} I_2 + H_2$$

$$LiNO_3 \xrightarrow{750°K} LiNO_2 + \tfrac{1}{2}O_2$$

The use of hydrogen as a general fuel or energy carrier is being widely discussed (*1*) because it is nonpolluting and can be produced from energy sources other than fossil fuels. However, if hydrogen is to become the fuel of the future, it will have to be produced economically in large quantities. Present methods of production include the cracking of natural hydrocarbons and the conversion of water either by reaction with coal or through electrolysis. Only by electrolysis can hydrogen be generated from water without a drain on fossil fuel reserves, provided the electricity for the process originates in plants that are not fossil fueled.

The electrolysis of water requires the conversion of the primary energy, be it heat (nuclear, geothermal, or solar) or hydrostatic head, into electricity. If the hydrogen is to be used to produce heat, the manner in which 80 percent of the energy is utilized in the United States, there will be a loss in efficiency by going through the electrolysis process. In addition, the generating and electrolysis equipment represent a large capital investment which will be reflected in the cost of the final product.

Quite aside from the cost aspect there is the problem of the availability of electrical power. If it were desired to replace the thermal equivalent of all the fossil fuel currently consumed in the United States by electrolytic hydrogen, the electrical generating capacity would have to be increased at least 15-fold, and if only nuclear-powered capacity is admitted, at least 150-fold. Clearly, an alternative process to the electrolytic decomposition of water must be developed if hydrogen is indeed to become the energy carrier of the future.

A thermochemical process not requiring conversion of primary heat or solar energy into electricity would be ideally suited for the purpose if it could be conducted at sufficiently low temperatures. Funk (*2*) has shown that for a thermochemical process to operate below 2500°K it must consist of several steps. Some progress in this direction has been made with the four-step "Mark I" cycle of de Beni and Marchetti (*3*), which operates at temperatures not exceeding 1000°K. This temperature appears realizable with high-temperature gas-cooled reactors. It is desirable, however, to develop a process capable of operating in the range of temperatures of present-day nuclear reactors, geothermal sources, and potentially even converters of solar to thermal energy.

We present here a three-step chemical cycle which has the potential of decomposing water at temperatures not exceeding 750°K. The three reactions composing the cycle are

$$LiNO_2 + I_2 + H_2O \xrightarrow{300°K} LiNO_3 + 2HI \quad (1)$$

$$2HI \xrightarrow{700°K} I_2 + H_2 \quad (2)$$

$$LiNO_3 \xrightarrow{750°K} LiNO_2 + \tfrac{1}{2}O_2 \quad (3)$$

The temperature at which each reaction proceeds is placed above the arrow. Reaction 1 serves to separate the products by forming two easily