Fig. 2. Power station at Four Corners, New Mexico.

of the mixing layer and were associated with a visibility of approximately 9.5 km (*2*).

Data for curve 6 were developed from a circular flight pattern through the plume of a coal-fired power station at Four Corners, New Mexico. Samples were taken about 6.5 km from the point of emission; visibility in the plume was estimated at less than 1.5 km. Figure 2 illustrates this plume. The photo was taken about 30 minutes prior to the sampling activities.

Although suspended particulates have been traditionally sampled and reported on a mass basis in air-pollution investigations, it is useful to know more about their size distribution and abundance (*3*). This is especially true when one considers the effects of aerosols on visibility and the resulting hazards to both air and ground traffic.

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References

1. K. T. Whitby and R. A. Vomela, *Environ. Sci. Tech.* **1**, 801 (1967).
2. G. C. Holzworth, *J. Appl. Meteorol.* **6**, 1039 (1967).
3. U.S. Department of Health, Education, and Welfare, Division of Air Pollution, *U.S. Public Health Serv. Publ. APTD 68-9* (1966); M. Corn, in *Air Pollution*, A. C. Stern, Ed. (Academic Press, New York, 1968), p. 47; C. E. Junge, *Air Chemistry and Radioactivity* (Academic Press, New York, 1963).

30 January 1969; revised 26 August 1969

Alpha-Recoil Tracks in Mica: Registration Efficiency

Abstract. *Recoils from alpha-particle decay of naturally occurring radioactive nuclides have energies between 70 and 169 kiloelectron volts. It is shown that these alpha recoils register tracks in mica, observable as etch pits, with an efficiency of about 80 percent. When the recoil energy is degraded to 40 kiloelectron volts the efficiency drops to 50 percent. But, since the decay of each thorium or uranium impurity atom in natural mica is followed by a cascade of six or eight alpha particles, the overall registration efficiency must be very nearly 100 percent.*

Huang and Walker (*1*) have reported that heavy nuclei recoiling during emission of alpha particles can produce etchable tracks in mica. Samples etched in 48 percent hydrofluoric acid showed many shallow etch pits which were made visible with phase-contrast microscopy. These tracks were attributed to α decay of uranium and thorium series impurities. This phenomenon was suggested as the basis of a method of age determination several thousand times more sensitive than fission track dating.

In identifying the source of these tracks Huang and Walker first annealed samples of mica at 600°C for 21 hours to remove latent fossil tracks. Then they evaporated solutions of Th^{228}, and

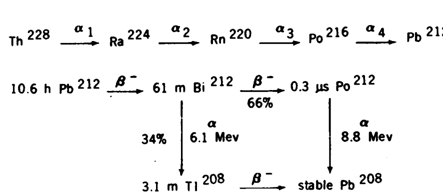


Fig. 1. The Th^{228} (1.9 y) decay chain.

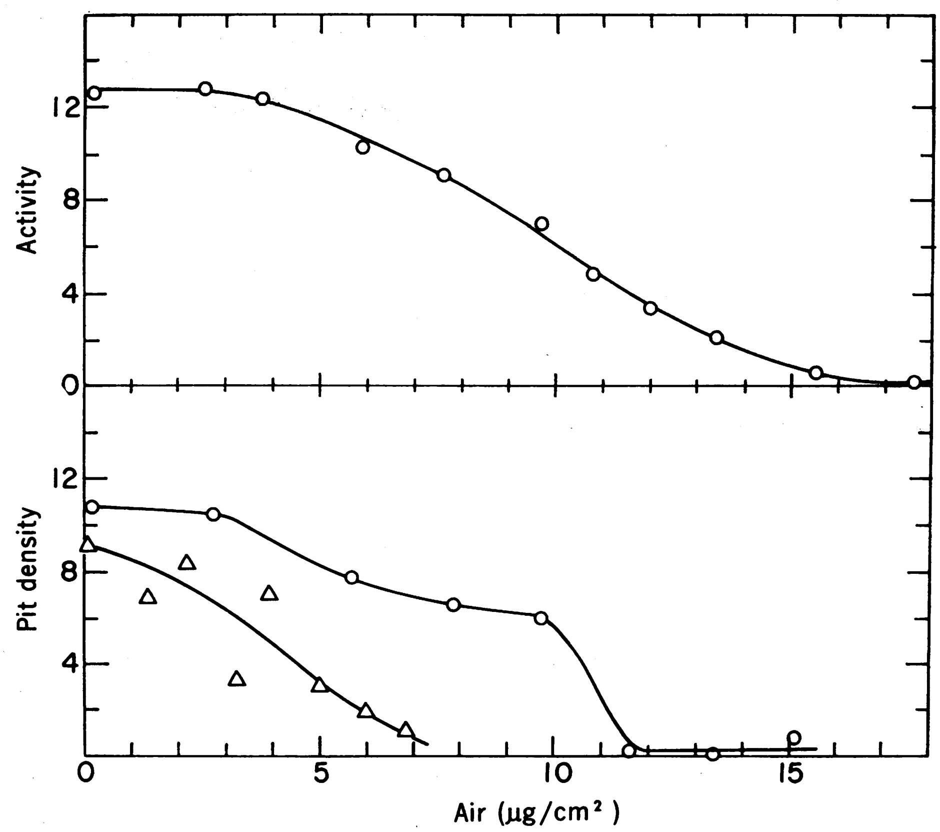
its decay products, on these samples. After a 20-hour irradiation and etching with 48 percent HF for 2 hours, they produced shallow pits identical in appearance with fossil pits. However, contact of annealed mica with uranium foils for up to 12 days did not yield appreciable densities of tracks. As a possible explanation of this apparent contradiction the authors suggested that radiation damage from several successive α recoils may be necessary to initiate growth of an etch pit. From a uranium source only a single α recoil is produced during the time of the experiment because the daughter products are long-lived. On the other hand, Th^{228} has a series of short-lived daughter products so that about five successive α recoils are produced in a 20-hour exposure.

This study was initiated to test this interpretation and to seek answers to the following questions. How many α recoils are required to initiate growth of an observable etch pit at a given site? What is the ratio of pits to incident recoil particles? What is the minimum α-recoil energy required to produce an etch pit?

The experiments were started with members of the Th^{228} (1.9 y) decay chain (Fig. 1). Sources of Pb^{212} (10.6 h) were collected on aluminum foils, as very thin active deposits, from decay of gaseous Rn^{220} (54 s) emanated by 2 mc of Th^{228} (*2*). Only one α particle is emitted per Pb^{212} decay: either 6.1 Mev or 8.8 Mev. In the first case the recoil energy is 117 kev and in the latter it is 169 kev. By counting the activity of Tl^{208} (3.1 m) it is possible to determine the number of recoils emitted by a source. Recoils from β^- emission have energies $< 10^{-4}$ that of α recoils, and, therefore, they do not leave the foil in significant amount.

The α recoils were collected on 1.5 cm^2 pieces of annealed mica placed 12 mm from the source inside a vacuum system. The mica rested on a thin brass frame such that only the central area (8×8 mm) was exposed to the source. A potential of +500 volts was applied to the frame to repel ions near thermal energy. Recoils were collected for 10-minute intervals on a series of mica squares. The air pressure in the system was varied between 0 and 10 torr so as to vary the energy of the recoils. After each 10-minute collection period the activity of Tl^{208} (3.1 m) on each piece of mica was measured with a calibrated end-window proportional counter. Thus the number

Fig. 2. Upper curve, integral range distribution in air of 117-kev Tl^{208} recoils as measured by their radioactivity. Lower curves, density of etch pits in annealed mica exposed to recoils degraded in energy by various thicknesses of air absorber; circles, 169-kev Pb^{208} + 117-kev Tl^{208}; triangles, 103-kev Pb^{206} from Po^{210} source. The ordinates are in arbitrary units.



of Tl^{208} recoils reaching the mica was determined in each case. For zero air absorber the number of Pb^{208} recoils collected could also be calculated since the branching ratio is known. These numbers were compared with the density of etch pits measured with a Wild phase-contrast microscope after the mica was etched for 3 hours in 40 percent HF.

The activity and etch pit densities were plotted as a function of air absorber (Fig. 2). The mean range of Tl^{208} activity is in agreement with Lindhard's calculation (*3*). At zero air absorber the radioactivity measurements indicated that the following numbers of recoils per square centimeter reached the mica: 0.9×10^5 Tl^{208} + 1.7×10^5 $Pb^{208} = 2.6 \times 10^5$ total. The measured density of the etch pits was 2.1×10^5 per square centimeter. A second duplicate experiment gave almost identical results. Since the experimental uncertainty was 10 to 15 percent in each measurement, it is not clear from these data alone whether both species registered pits with high efficiency or whether most of the tracks resulted only from 169 kev Pb^{208}. However, consideration of the absorption curve in Fig. 2 (lower) shows that the 117-kev Tl^{208} must also register with a high probability. The etch pit density decreases only modestly up to ~ 10 $\mu g/cm^2$ air absorber, a thickness which degrades 169-kev recoils to ~ 40 kev (*3*). The apparent double plateau in the absorption curve may be indicative of the two groups of recoils, 117 kev and 169 kev; however, a duplicate run did not exhibit this effect. The etch pits on the mica surface become less distinct as the energy of the recoils is decreased. Therefore, the shape of the absorption curves depends somewhat on the ability of the observer to see pits of very low contrast. Undegraded recoils give pits of adequate contrast (Fig. 3). Thus it is established that in the Pb^{212} series single recoils from α decay register with high efficiency.

Similar results were obtained from experiments with thin sources of Po^{210} (*2*) which emit 103-kev recoils of Pb^{206} (Fig. 2; Fig. 3, C and D). From the measured α activity of the sources and from the density of etch pits observed in the mica at zero absorber, it was calculated that these recoils record with an efficiency of ~ 80 percent. As recoil energy is reduced, registration efficiency decreases, as does contrast of the etch pits. Efficiency drops to ~ 50 percent at 40 kev, in agreement with the results from the Pb^{212} sources.

An attempt to produce tracks in mica with 80-kev α recoils from a mixed $U^{234,5}$ source (*2*) yielded negative results. Various small amounts of

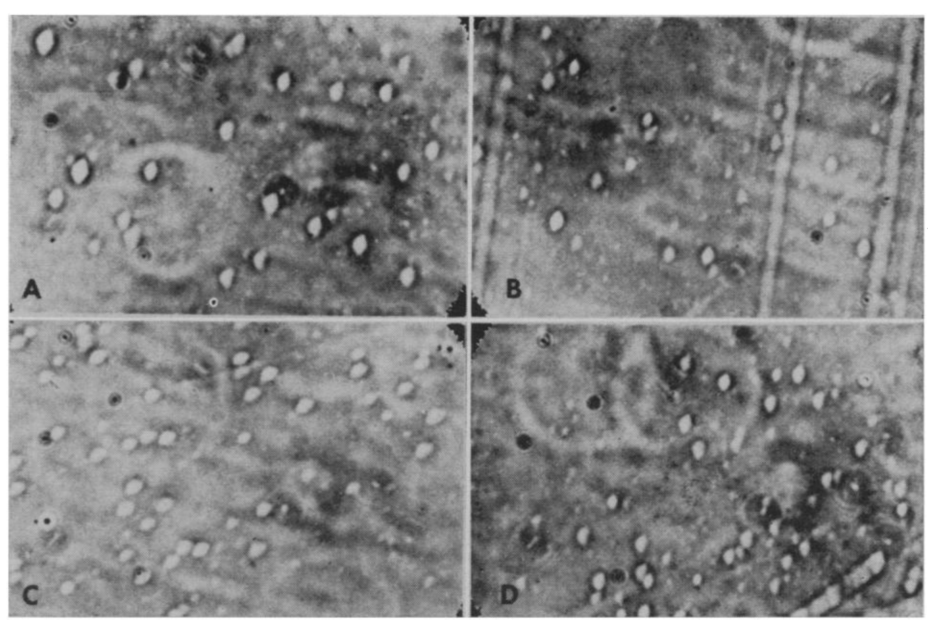


Fig. 3. Alpha-recoil tracks taken with a Wild phase-contrast microscope. (A) 117-kev Tl^{208} and 169-kev Pb^{208} recoils, undegraded. (B) Tl^{208} and Pb^{208} degraded by 5.5 $\mu g/cm^2$ air. (C) 103-kev Pb^{206} recoils from Po^{210} source. (D) Pb^{206} recoils degraded by 2.0 $\mu g/cm^2$ air. Density in (A) and (B) is $\sim 2 \times 10^5$ per square centimeter; in (C) and (D), $\sim 4 \times 10^5$. The diamond-shaped etch pits are the α-recoil tracks; the indistinct dots are from background defects in the mica.

enriched uranium, 5 to 50 $\mu g/cm^2$, were evaporated onto annealed pieces of mica. Each was then covered with a second piece, and these samples were placed in vacuum for periods varying from 16 hours to 6 days. The uranium deposits were dissolved off with nitric acid, and both pieces of mica from each sandwich were etched with 40 percent HF for 3 hours. No appreciable increase in etch pit density was seen above background. Based on α counting of the samples, the limit was < 1 percent of the density expected for an infinitely thin source. Presumably the evaporated deposits were thicker than indicated, and there may have been surface films which prevented the recoils from reaching the mica with sufficient energy to give observable tracks.

In natural samples of mica with dissolved U and Th impurities, there is no problem with surface deposits. In each decay chain a series of six or eight α particles is emitted, and the recoils vary in energy between 70 and 169 kev. The probability is about 80 percent that each recoil will register a track. If there is no appreciable diffusion of daughter products in the mica, each cascade of α recoils will register as a single fossil track with virtually 100 percent efficiency. Thus, the α-recoil method of dating mica should be as reliable as fission track dating but three orders of magnitude more sensitive.

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References and Notes

1. W. H. Huang and R. M. Walker, *Science* **155**, 1103 (1967).
2. Radioactive sources were prepared by Y. Sapir of the Soreq Nuclear Research Center, Yavne, Israel.
3. J. Lindhard, M. Scharff, H. E. Schiøtt, *Kgl. Dan. Vidensk. Selsk. Mat. Fys. Medd.* **33**, No. 14, 1 (1963).
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Gravity: First Measurement on the Lunar Surface

Abstract. *The gravity at the landing site of the first lunar-landing mission has been determined to be 162,821.680 milligals from data telemetered to earth by the lunar module on the lunar surface. The gravity was measured with a pulsed integrating pendulous accelerometer. These measurements were used to compute the gravity anomaly and radius at the landing site.*

A gravity measurement at one point on the surface of the moon can be used for the following purposes. (i) If the lunar gravity measured is very different from normal (theoretical) gravity, it would suggest the order of magnitude of other anomalies to be expected and, perhaps, would provide a guide for future surveys; (ii) the difference between the observed gravity and the gravity for a homogeneous moon indicates the degree of homogeneity of the moon; and (iii) the radius of the moon at an observation point can be determined independently of other methods of measurement.

To obtain the gravity anomaly, the radius at the observation point must be assumed. In the determination of the radius, it is assumed that the measured value of gravity is a representative value, unaffected by anomalies; the radius is treated as an unknown. In the determination of the gravity anomaly, the radius is treated as a known quantity and is used to compute normal gravity. The normal gravity may then be compared with the observed gravity.

Because of the limitations imposed on scientific experiments by constraints on the mass load and on the time available to the crew for scientific experiments during the first lunar-landing mission, it is very important to deduce as much information of scientific value as possible from tasks performed for operational reasons. The data used to determine gravity were collected primarily for operational reasons and were telemetered to earth from the lunar module on the lunar surface.

The format of the telemetered data is controlled by the lunar module guidance computer. The coast-and-align format contains the actual readings from the pulsed integrating pendulous accelerometer (PIPA). The PIPA is a system for the measurement of acceleration and velocity which can be synchronized with a digital computer. The PIPA readings are velocity increments along the inertial measurement unit (IMU) (stable member) X-, Y-, and Z-axes. The IMU is the main unit of the Apollo inertial guidance system, consisting of a stabilized platform (inertial platform) which contains (i) three inertial reference-integrating gyroscopes and (ii) three PIPA's. The IMU can determine any attitude changes or accelerations of the spacecraft. An inertial reference-integrating gyroscope is one with a single degree of freedom which senses displacement of the stable platform on which it is mounted and generates signals accordingly. Measurements of gravity on the earth with accelerometers have been described by Bock and Wing (*1*), Bowin *et al.* (*2*), and Wing (*3*).

The PIPA readings along the X-, Y-, and Z-axes are designated by PIPAX, PIPAY, and PIPAZ, respectively. The PIPA's were zeroed every 81.93 seconds while the lunar module was on the lunar surface. The PIPA readings are given in stable-member coordinates. The nominal value of one PIPA is 1 cm/sec.

On the basis of this nominal value, the magnitude of the gravity vector g (to a first approximation) can be computed as follows:

$$g = \left[\left(\frac{XI}{\Delta T}\right)^2 + \left(\frac{YI}{\Delta T}\right)^2 + \left(\frac{ZI}{\Delta T}\right)^2 \right]^{1/2} \qquad (1)$$

where

$$XI = X_2 - X_1$$
$$YI = Y_2 - Y_1$$
$$ZI = Z_2 - Z_1$$
$$\Delta T = T_2 - T_1$$

Accelerometer readings from two discrete times are used. The PIPA's were read every 2 seconds; however, it is better that there be as much time difference as possible between readings for the computation of gravity. For example, while the lunar module was on the lunar surface, the PIPA's were read at 123 hours 26 minutes 52 seconds (time T_1). Thus X_1 equals the PIPAX reading at T_1, Y_1 equals the PIPAY reading at T_1, and Z_1 equals the PIPAZ reading at T_1. The PIPA's were read at 123 hours 28 minutes 12 seconds (time T_2). Thus X_2 equals the PIPAX reading at T_2, Y_2 equals the PIPAY reading at T_2, and Z_2 equals the PIPAZ reading at T_2. The quantities XI, YI, and ZI represent the changes in the PIPA's during the 80 seconds. To determine the PIPA readings for 1 second, the PIPA reading for the entire time interval is divided by ΔT in seconds.