# Evidence for Heavy Nuclei in the Primary Cosmic Radiation

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RECENT high altitude flights in free balloons have given evidence for the existence of nuclei of atomic number up to about 40 and kinetic energies of about $\frac{1}{2}$ Bev per nucleon as a component of cosmic radiation above 90,000 feet.

Tracks of such particles were observed both in a cloud chamber and in Ilford nuclear emulsions.

The cloud chamber and associated equipment was enclosed in a sphere of aluminum 30 inches in diameter and 0.040-inch thick, which was kept at atmospheric pressure and within a temperature range between 58 and 98 degrees F throughout the flight. The balloon reached an altitude of 94,000 feet (14 g/cm$^2$ below the top of the atmosphere), spent three hours above 90,000 feet, and four hours above 65,000 feet.

Stacks of photographic plates in groups of twelve were placed above and below the chamber, the emulsion lying in the vertical plane. Tracks which entered the photographic plates below the chamber within 30° from the vertical had to pass through all or part of the four $\frac{1}{4}$-inch lead plates placed in the chamber.

In the photographic plates we observed tracks many times denser and heavier than those which are obtained from fragments produced in nuclear explosions. A further feature which clearly distinguishes these tracks from those produced by ordinary nuclear fragments is the very large number of slow electrons ($\delta$-rays) issuing from the dense and completely solid filament of silver grains which constitutes the core of the tracks. Figures 1, 2 and 3 show examples of such tracks. For comparison, Fig. 4 shows tracks of a $\pi$-meson, three protons, and a $Li^8$ nucleus disintegrating into two slow $\alpha$-particles. All tracks are reproduced at the same magnification.

Most of these tracks pass through the entire stack of plates and can be followed from one emulsion to the next after penetrating the 1.4-mm thick glass backing of the plates. Not all of the penetrating tracks are equally heavy; some are only slightly heavier than those of slow $\alpha$-particles, but their ranges are about 1000 times larger.

In cases where the angle is favorable, the track may be pursued through all twelve plates, and tracks have been observed whose range is certainly greater than 7.5 cm of glass or 20 g/cm$^2$. If one combines this information with the observation that these tracks are everywhere much heavier than $\alpha$-particles near the end of their range and that, therefore, at no point of the track is the energy loss smaller than 0.6 Mev/(mg/cm$^2$), one obtains for such a track a minimum charge $Z=16$ and a minimum kinetic energy $E=13$ Bev. Actually, since for many of these tracks the central core of developed silver grains is more than three times as wide as the corresponding core for slow $\alpha$-particles, the minmum energy loss is probably in the neighborhood of nine times 0.6 Mev/(mg/cm$^2$) or 5.4 Mev/(mg/cm$^2$).

As an example, we now consider a track which enters plate No. 3 at an angle of 37° with the vertical and stops in the glass between plates No. 10 and 11. This particle has a range of 1.5


FIG. 1. A very heavy track produced by a particle (estimated $Z=40$) with a range of 1.5–1.9 cm of glass. Four $\delta$-rays can be distinguished in the 10-micron path length shown in the photograph.


FIG. 2. Another heavy track showing a large number of δ-rays.

cm to 1.9 cm in glass. Assuming an energy loss, at the point where the track enters the stack of plates, of 4 Mev/(mg/cm$^2$) and 6 Mev/(mg/cm$^2$), respectively, we obtain the limits for the energy and charge of this particle given in columns 2 and 3 of Table I.

If we assume that this particle entered the atmosphere from the outside, it must have passed through $14/\cos 37° \text{ g/cm}^2 = 17.5 \text{ g/cm}^2$ of air, where it must have lost the energy given in column 4 of the table. Column 5 gives the kinetic energy with which the particle entered the top of the atmosphere. Column 6 shows the cut-off energy for such particles due to the sun's magnetic field. (If one assumes that the sun's field is responsible for the knee of the latitude curve at $\lambda = 48°$, and that the cut-off kinetic energy for protons is 2.3 Bev.)

Comparison of columns 5 and 6 shows that the initial energy assigned is indeed sufficiently high to permit the particle to penetrate the sun's magnetic field.

Another example is provided by the track shown in Fig. 5 which is a stereophotograph of a penetrating heavily ionizing particle taken at 94,000 feet in the twelve-inch cloud chamber filled with argon at 110-cm pressure. The chamber was temperature compensated by a scheme modified from that of Leighton.[1] At the time the

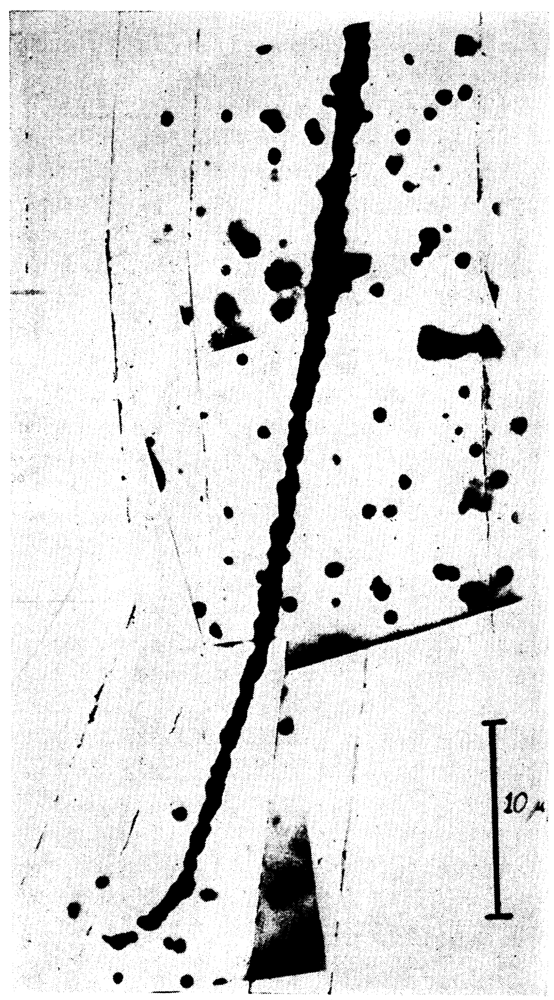


FIG. 3. A medium heavy track ($Z \sim 10-15$) ending in the emulsion. The particle has a low velocity; δ-rays are almost entirely absent. Thinning of track towards the end of the range suggests gradual filling of electronic shells.

[1] R. B. Leighton, Rev. Sci. Inst. 19, 274 (1948).

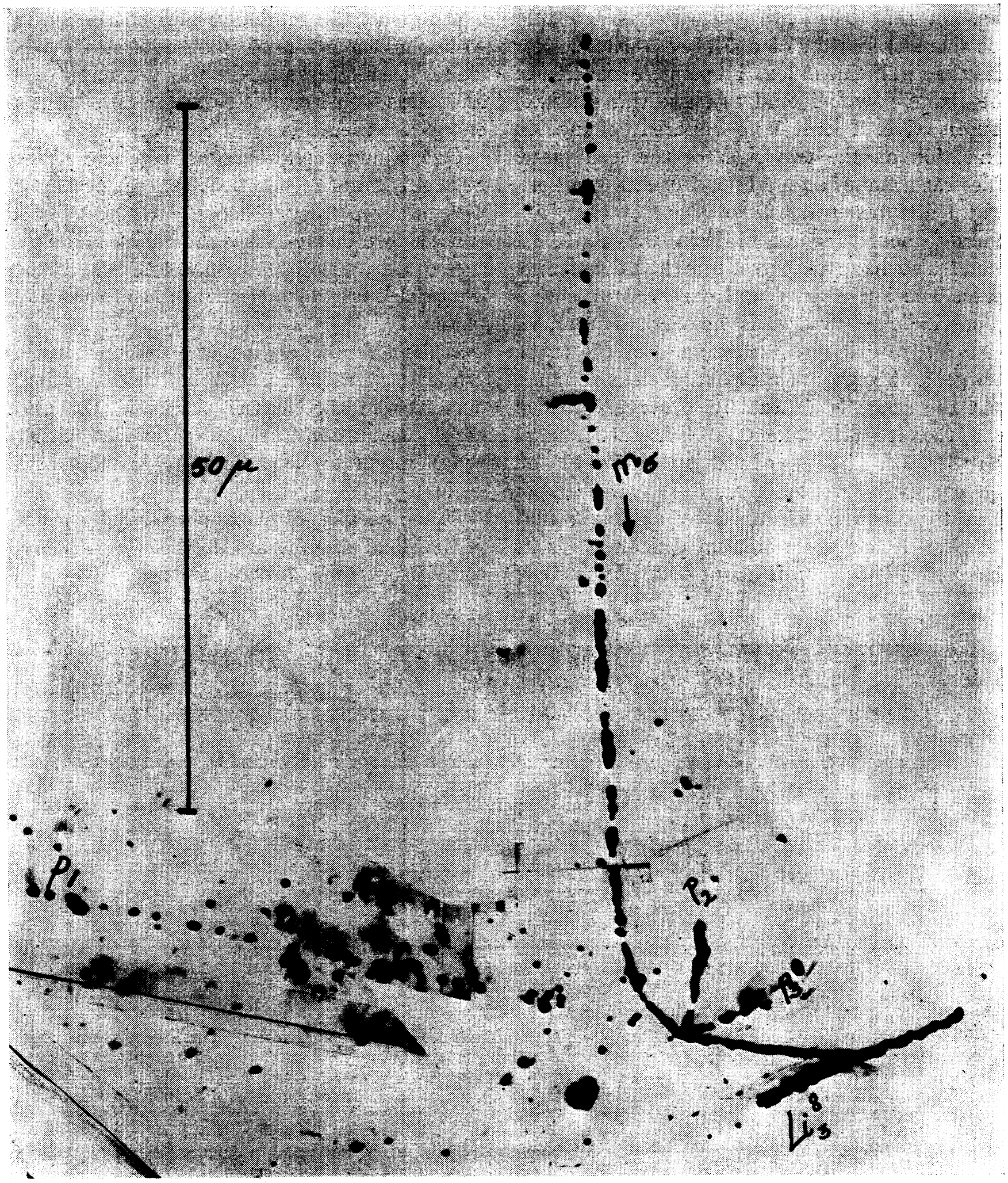


FIG. 4. Nuclear disintegrations produced by a slow meson showing tracks of fast protons, slow proton, slow $\pi$-meson, $Li^8$ nucleus disintegrating into two slow $\alpha$-particles.

photograph was taken the temperature was rising and compensation had not been completely established, hence the chamber was under-expanded. The ionization was estimated by a comparison with alpha-tracks taken in the same chamber, at the same pressure, with the same gas. On that basis the ionization is probably not more than that of a 5-Mev $\alpha$-particle nor less than half this much. The underexpansion of the chamber would tend to make this estimate conservative. There is no apparent change in ionization on the two sides of the lead plate. The track makes an angle of 49° with the horizontal and penetrates 9.56 g/cm$^2$ of lead. Assuming that it comes in from the above, it would also have to pass through 2.4 g/cm$^2$ of glass. The ion density and observed minimum range indicate that it is heavier than an $\alpha$-particle. To establish an estimate of the mass, charge, and energy of the particle, it is assumed that the range is at least its observed path in lead, that it ionizes like a 5 Mev $\alpha$-particle, and that $M=2Z$. The lower limit is then $Z=12$ and the energy is greater than 5 Bev. An upper limit to $Z$ can be obtained by assuming that the particle has the minimum ionization for its charge. Its ionization is about 400 times that of a proton at the minimum and consequently it would have a charge of $(400)^{\frac{1}{2}}$ or $Z=20$. We conclude, therefore, that if the estimate of the ionization is correct, $12<Z<20$ and that the energy is at least as great as 5 Bev.

One hundred photographs were taken above 80,000 feet and several heavily ionizing particles were observed in the cloud chamber, but the track shown in Fig. 5 was the only unambiguous case of a particle which ionized as heavily as an $\alpha$-particle and which certainly penetrated a lead plate.

We shall now discuss the evidence for the primary character of this radiation, confining ourselves to the heavier tracks in the photographic emulsion (i.e., those which exhibit a completely unbroken column of developed silver grains).

In the package of plates placed above the lead of the cloud chamber, we have so far observed a total of 50 tracks (about one per cm$^2$ in a 3–4-

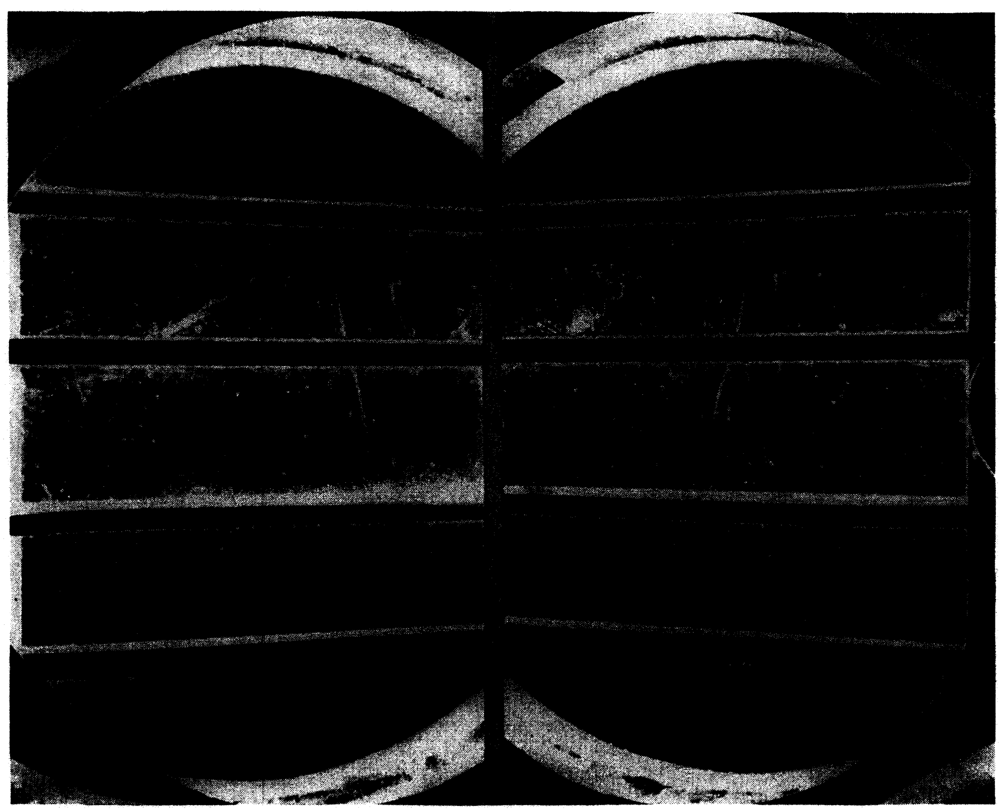

FIG. 5. Cloud-chamber stereophotograph of heavily ionizing penetrating particle taken at 94,000 feet.

TABLE I.

| 1 Energy loss in Mev/(mg/cm$^2$) when entering stack of plates | 2 Kin. energy in Bev when entering stack of plates | 3 Atomic number $Z$ | 4 Energy loss in 17.5 g of air | 5 Kin. energy at top of atmos. | 6 Energy necessary for penetrating solar magnetic field |
|---|---|---|---|---|---|
| 4 | $22<E<26$ | $39<Z<41$ | 61 Bev | 85 Bev | 69 Bev |
| 6 | $35<E<41$ | $49<Z<52$ | 88 Bev | 126 Bev | 88 Bev |

TABLE II.

| 1 Angle of incidence $\theta$ | 2 Percentage of tracks | 3 Average flux per cm$^2$ per second and steradian |
|---|---|---|
| $0<\theta<30°$ | 30% | $1.4\times10^{-4}$ |
| $30°<\theta<60°$ | 60% | $0.51\times10^{-4}$ |
| $60°<\theta<90°$ | 10% | $0.04\times10^{-4}$ |

hour exposure). The angular distribution with respect to the zenith is given in column 2 of Table II. Taking into account the variation of the effective area of the plates with angle of incidence, we obtain the average flux per cm$^2$ per second and per unit solid angle. The values for the three angular intervals indicated are given in column 3 of Table II.

(a) The rapid decrease of flux with zenith angle is not compatible with the assumption that these particles are secondaries produced for instance by protons of $\sim10^{11}$ ev, because the angular distribution of protons of this energy must be almost isotropic at this altitude.

(b) Since the intensity is greatly reduced by increasing the thickness of air traversed from 14 g/cm$^2$ at $\theta=0°$ to 28 g/cm$^2$ at $\theta=60°$, the majority of these particles must have at 94,000 feet a remaining range of less than 14 g/cm$^2$. This is confirmed by comparing the number of tracks observed in plates below and above the 1 inch of lead in the cloud chamber. The number of tracks below the lead is smaller than the corresponding number above the lead by about a factor of 6. All but one of the 13 particles observed below the lead enter from outside the cone subtended by the lead plates.

The lead difference also confirms the previous conclusion that the particles are not secondaries produced in the lead plates.

(c) Further confirmation that these particles are much more rapidly absorbed than primary protons was obtained from an earlier flight of one-hour duration at an altitude between 57,000 and 69,000 feet (50 g/cm$^2$ of air). In this flight the plane of the emulsion was horizontal. No very heavy tracks were observed. However, in 30 square centimeters of emulsion three tracks were observed which penetrated at least one glass plate and which ionize only slightly more than $\alpha$-particles.

The sun's magnetic cut-off is high enough such that all particles of $Z<40$ which enter the top of the atmosphere from the zenith will penetrate to 94,000 feet. Therefore, we may assume that the flux on top of the atmosphere is of the same order of magnitude as the flux incident normally at 94,000 feet ($1.4\times10^{-4}$ particles per cm$^2$ per second and unit solid angle). This corresponds to about one heavy particle for 1000 primary protons, an intensity ratio which is not inconsistent with the assumed relative abundance of heavier atoms ($Z>15$) of the Russel mixture.

We wish to extend our thanks to the Office of Naval Research for its support, to the Aeronautical Research group of General Mills for their cooperation, to the pilots from the Wold Chamberlain Air Base who have assisted in recovering the apparatus, to Mr. Tom Putnam for help in preparing the photographs, and to Dr. R. E. Marshak, Dr. J. T. Tate, and Dr. J. Weinberg for helpful discussions.


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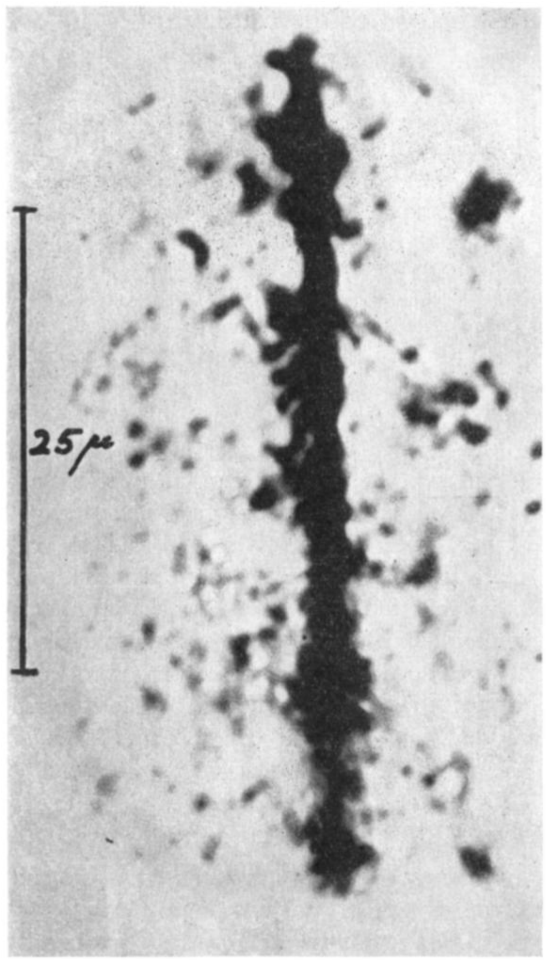


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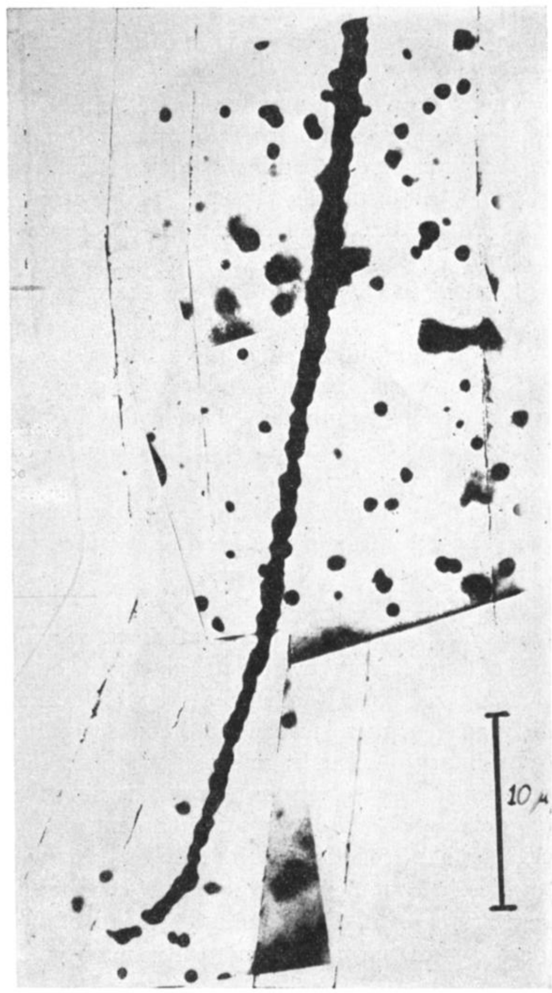


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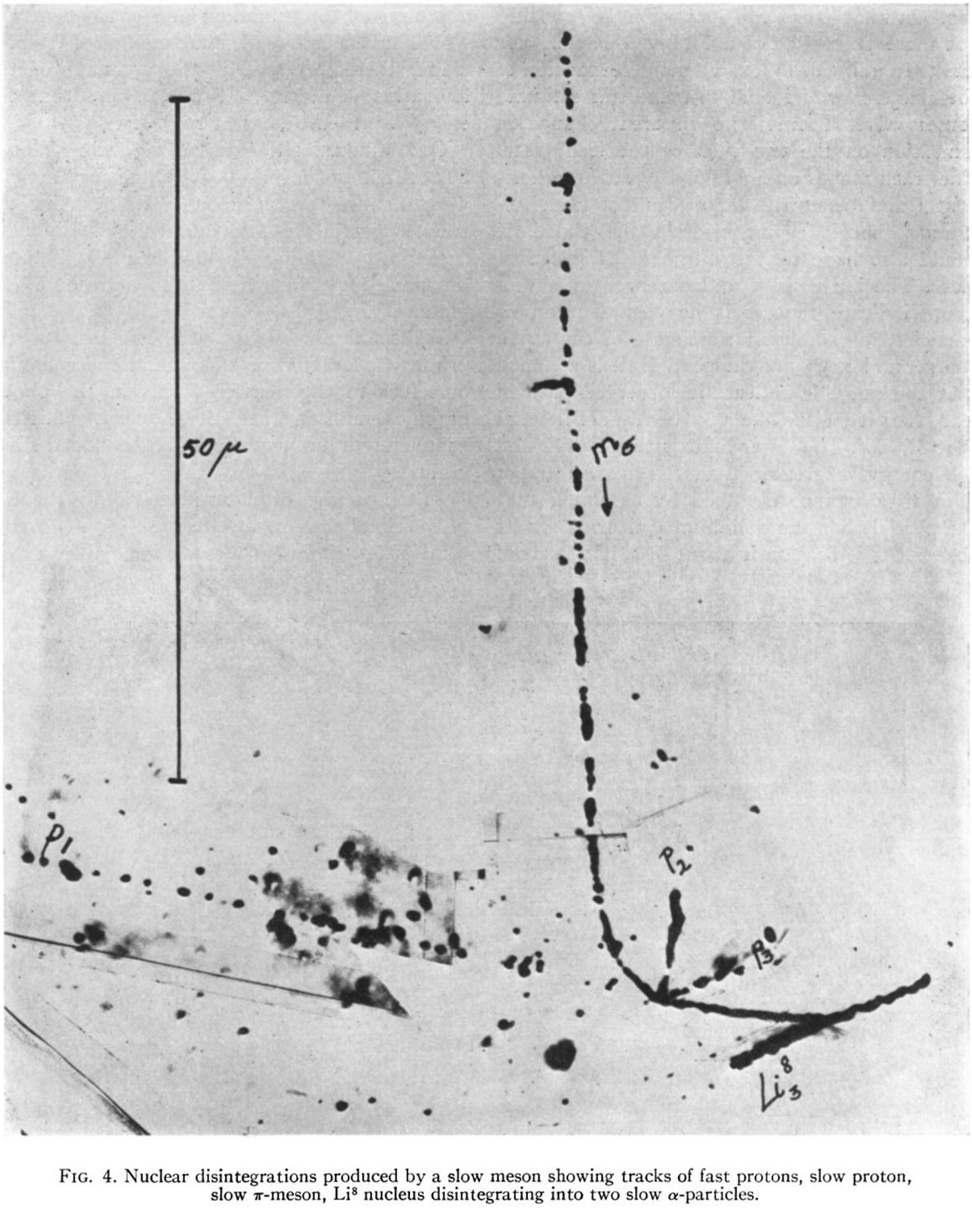


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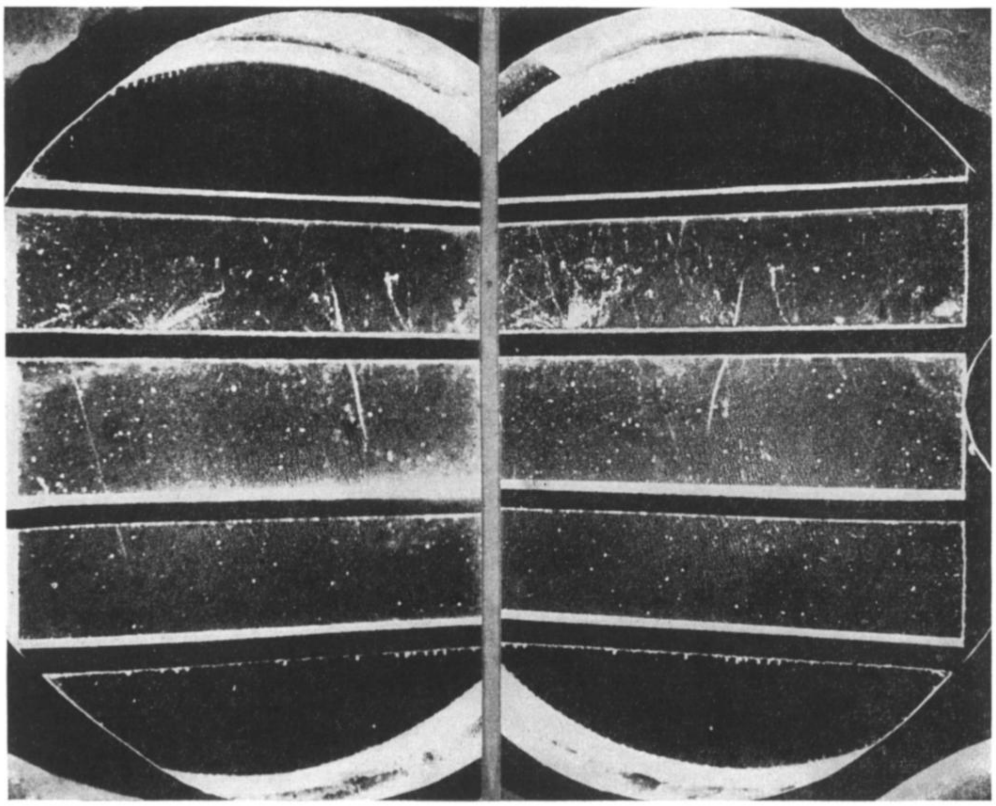

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