Grain-Spacing of Alpha-Ray, Proton and Deuteron Tracks in Photographic Emulsions

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A statistical study has been made of the grain-spacing of alpha-ray, deuteron and proton tracks in an Ilford *R* 2 emulsion with standardized processing and viewing technique. The alpha-rays were from ThC and ThC′ and the deuterons and protons from cyclotrons. A theoretical explanation of the difference in grain spacing is given and some applications of the technique in the study of cosmic rays and nuclear research.

FOR nearly thirty years it has been known that alpha-particles in passing through photographic emulsions make tracks consisting of rows of silver grains.[1] These tracks can be seen if the emulsion is developed and viewed through a microscope with magnification and illumination adequate to reveal the individual grains. A fine-grained emulsion of the process (or lantern slide) type with average grain size of somewhat less than 10^{-4} cm radius gives well-defined tracks of rather uniformly spaced grains as shown in Fig. 1. A statistical study of the spacing of the grains in these alpha-ray tracks was made by W. Michl[2] as early as 1912. He concluded (a) that the number of silver grains in a track was directly proportional to the length of the track and (b) that both the number of silver grains in the tracks and the lengths of the tracks were directly proportional to the residual air range which the particles had on entering the emulsion.

More recently tracks due to protons (obtained by bombarding beryllium by alpha-particles) were studied.[3] It was noticed by all workers (a) that the grain-spacing was distinctly larger for proton tracks than for alpha-rays, (b) that the spacing was not uniform but was greater the higher the speed of the particle and (c) that the actual spacing depended on the photographic emulsion used.

Obviously if the photographic emulsion was found to distinguish thus simply between these fundamental atomic particles of nuclear physics, it became highly important to obtain data on grain-spacing for some standard emulsion, processing, and viewing technique, and secondly to attempt to formulate some theoretical explanation for this variation in spacing which was so unexpected by those who thought that either type of projectile must affect the same number of grains in a given length, *viz.* the number which were encountered by the particle—a supposedly fixed number for a given emulsion.

In addition to a study of the spacing in alpha-particle and proton tracks the present work includes data on deuteron tracks not previously reported. The emulsion chosen as a standard was the Ilford R2 which was found to have the right grain size to give tracks for all three types of particles.

EXPOSURE OF THE PLATES

Alpha-rays

Two plates of usual microscope slide size (1×3 inches) were stood on edge, emulsion to

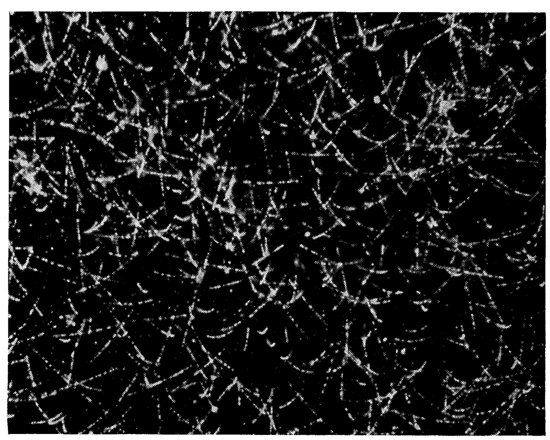


FIG. 1. ThC′ and ThC tracks in the Ilford R2 emulsion. (mag. 225 diam.)

[1] O. Mugge, Zentralbl. f. Mineralogie **71**, 144–147 (1909).
[2] W. Michl, Akad. Wiss. Wien Ber. IIa **121**, 1431–1447 (1912).
[3] E. Mühlestein, Arch. d. Sci. Phys. et Nat. **4**, 38–63 (1922). M. Blau, Mitt. d. Ra. Inst. Nr. 179 (1925); 208 (1927), 259 (1930); Zeits. f. Physik **34**, 285–295 (1925); Akad. Wiss. Wien Ber. IIa, **134**, 407–436 (1925); IIa, **136**, 469–480 (1927); IIa, **139**, 327–347 (1930). A. Jdanoff, J. de phys. et le rad. **6**, 233–241 (1935). H. J. Taylor, Proc. Roy. Soc. **A150**, 382–394 (1935).

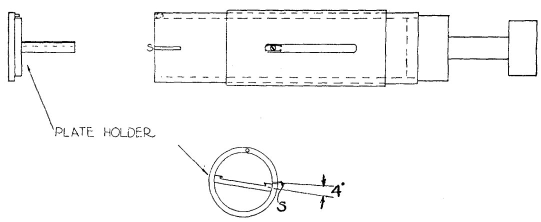


FIG. 2. Camera for cyclotron.

emulsion, and separated by a few thousandths of an inch. A button coated with the active deposit from thorium emanation gave a source of ThC and ThC′ alpha-particles. This button held immediately below the edge of the plates for about one minute gave several hundred quite flat tracks in the emulsions.

Protons and deuterons

The sources of protons and deuterons were the cyclotrons at the University of Rochester and Michigan, respectively. The plates were exposed in a simple sliding-tube "camera" shown in Fig. 2 which could be placed in the beam. The plateholder P fits into the camera tube so that the stream of particles which enters the camera from the side through the fine slot s strikes the plate at an angle of about four degrees to the surface of the emulsion. In this way flat tracks are secured. The outer tube provides a tight cover except during the instant of exposure. Because of the intensity of the cyclotron beams the exposures must be as short as possible.

Processing and Viewing Technique

The plates were processed in an Elon-hydroquinone process developer (Kodak formula D-11) for 3 min. at 65°F, and fixed in an acid hardening fixing bath (Kodak formula F-5). After washing and drying, the plates were mounted on a microscope equipped with a dark-field (cardioid) condenser, a 4 mm (N.A. 0.85) dry objective (uncorrected for cover-glass) and a 20× hyperplane eyepiece with an eyepiece scale of 100 divisions, each interval covering 2.35 microns on the microscope stage. The objective was equipped with a variable iris diaphragm which varied the illumination and the depth of field. The magnification of the complete system was 900 diameters. Tracks photographed through such a system are almost restored to air-ranges since the stopping power of this emulsion as compared with air for alpha-rays is about 1380. An oil-immersion objective increases the magnification about twice but its use necessitates the placing of oil on the surface of the emulsion. During the removal of this oil the emulsion tends to become scratched. The advantage that an oil-immersion objective has over an ordinary 4-mm objective with respect to differential focusing is almost completely overcome by the addition of the variable diaphragm in the tube of the 4-mm objective. A thin film of oil of cedar was used between the dark-field condenser and the glass side of the photographic plates.

If dark-field illumination is used the thickness of the plate must be such that the cone of light from the condenser comes to a focus in the emulsion. The emulsions were therefore coated for us by the manufacturer on glass about 1 mm thick.

Examination of Plates

The three types of tracks were examined under a magnification of 900 diameters. The variable diaphragm was set fairly wide open so that shallow focusing was obtained. Only those tracks which were entirely in focus under this condition were measured. The directions of the tracks were known from the method of exposure. All measurements were made from the slow end of the track. The number of grains in each five divisions of the eyepiece scale was counted. Data were obtained on approximately 260 tracks of each of the three radiations studied. All the data for the proton and deuteron tracks came from single plates while the data for the alpha-particles are from two plates exposed and processed together.

TABLE I. *Group data for alpha-particle tracks. Arithmetic means of grain number between scale divisions (1 eyepiece scale div.* = *2.35 microns).*

Group	No. of Tracks	No. of Grains in Successive Sections of Tracks 0–5	5–10	10–15	15–20	20–25	25–30	30–35
I	3	8.7						
II	60	8.5	7.0					
III	12	8.3	7.2	7.0				
IV	127	8.3	7.0	6.7	6.5			
V	58	7.9	7.0	6.6	6.6	6.8		
VI	0							
VII	1	7.0	6.0	4.0	5.0	5.0	4.0	7.0

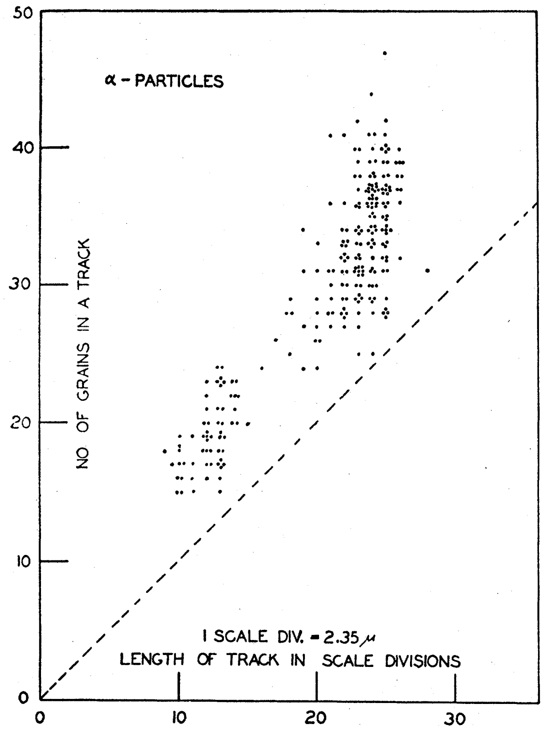


FIG. 3. Distribution of data for alpha-tracks.

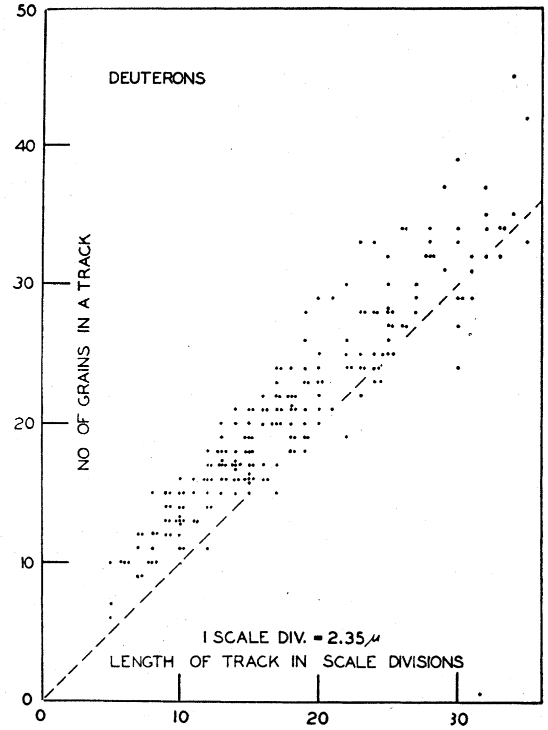


FIG. 4. Distribution of data for deuteron tracks.

RESULTS

The data are grouped according to the length of the tracks. Group I refers to those tracks whose lengths, l, satisfy the condition 5 div. $\leqq l < 10$ div. For Group II 10 div. $\leqq 1 < 15$ div., etc. The arithmetic means of the numbers of grains in each group were computed and are summarized in Tables I–IV. The distribution of the data is shown in Figs. 3, 4 and 5. A rather clear separation is shown for alpha- and proton tracks even in this distribution data. The data are averaged in Fig. 6 and well-separated curves are shown passing nicely through the observed values.

The average grain separations, obtained by dividing the track length by the number of grains minus one, are summarized in Table V.

TABLE II. *Group data on deuteron tracks.*

Group	No. of Tracks	No. of Grains in Successive Sections of Tracks							
		0–5	5–10	10–15	15–20	20–25	25–30	30–35	35–40
I	37	7.4							
II	60	7.3	5.7						
III	64	7.3	5.4	5.0					
IV	37	7.0	5.4	5.3	4.8				
V	32	7.1	5.6	5.0	4.4	5.3			
VI	23	7.2	5.4	4.7	4.4	4.7	4.9		
VII	5	7.2	5.4	5.2	5.6	4.8	4.4	5.0	
VIII	1	6.0	4.0	2.0	5.0	5.0	4.0	4.0	7.0

TABLE III. *Group data for proton tracks.*

Group	No. of Tracks	No. of Grains in Successive Sections of Tracks			
		0–5	5–10	10–15	15–20
I	60	5.8			
II	89	5.3	4.1		
III	76	5.2	3.7	4.2	
IV	36	5.2	3.6	3.5	3.5

TABLE IV. *The average number of grains in successive sections of tracks.*

	Av. No. of Grains in Successive Sections of Tracks							
	0–5	5–10	10–15	15–20	20–25	25–30	30–35	35–40
Alpha-Particles	8.3	7.0	6.7	6.5	6.8			
Deuterons	7.2	5.5	5.0	4.6	5.0	4.8	4.8	7.0
Protons	5.4	3.9	4.0	3.5				

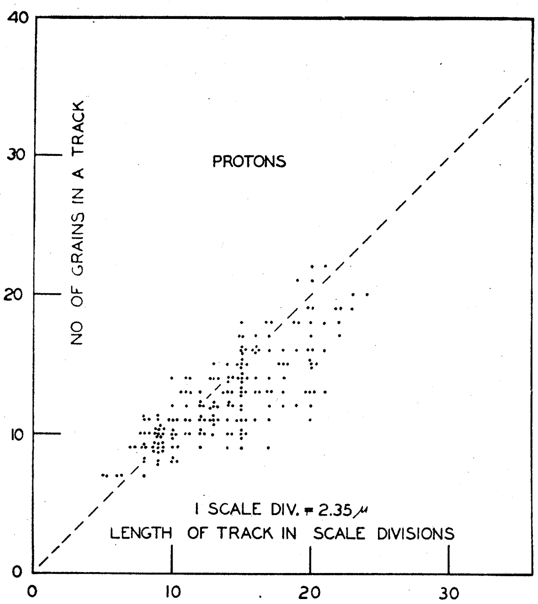


FIG. 5. Distribution of data for proton tracks.

SUGGESTED THEORY OF VARIATION IN GRAIN-SPACING

In his derivation of the equations for the photographic density produced by alpha-rays falling on a photographic emulsion, Wilkins[4] assumed that the alpha-particle rendered a grain developable if it came within a radius of action ρ and showed that this distance for the grains in the process emulsion used was about 0.6×10^{-4} cm at room temperature. The grain is pictured as becoming developable because the "impulse" (force$\times$time) exerted on an electron in the halide grain is able to eject an electron and ionize the grain. The radius of action will thus be a function of the speed of the projectile. The decrease in grain spacing results because as the projectile slows down, the radius of action is increased. Thus surrounding the track of an atomic projectile we have a cone of action, smaller when the speed of the particle is large and increasing in radius as the particle slows down.

TEST OF THEORY

A. Comparison of alpha- and proton spacing

The equation given by Bloch for the rate of loss of kinetic energy T by a particle of charge e and velocity V passing through a medium consisting of atoms of nuclear charge Ze is

$$-\frac{dT}{dx}=\frac{4\pi e^2NZ^2e^2}{mV^2}\log\frac{4\pi mV^2}{kZRh},$$

where Z is the atomic number of the element, R the Rydberg constant, N the Loschmidt number, k an undetermined constant, and m the mass of the electron.[5] From this equation, it will be noticed: (1) that the rate of loss of energy by an alpha-particle will be four times as great as for a proton of the same speed; (2) that since an alpha-particle has four times as much energy as a proton of the same velocity, but loses this energy at four times the rate, the ranges will be equal. We can, therefore, compare alpha-particles and protons of the same residual range and assume that their speeds are the same.

Calculation of radius of action and relative grain-spacing.—The force exerted by a projectile of charge E on an electron of charge e at a distance ρ is Ee/ρ^2 and the impulse is Ft. At the limiting distances ρ_α, and ρ_p the impulses due to an alpha-particle and a proton are to be equal but since the speeds are equal, we write

$$2e\cdot e/\rho_\alpha^2=e\cdot e/\rho_p^2,$$

whence

$$\rho_\alpha^2=2\rho_p^2$$

and hence the number of grains per unit path (being proportional to ρ^2) will have the ratio

$$n_\alpha=2n_p.$$

The grain-spacing is not exactly the reciprocal of the number of grains per unit path but is obtained by dividing the length of path by $n-1$. Thus the grain-spacing of protons should

TABLE V. *The average grain separation (in microns) (1 eyepiece div. = 2.35 microns).*

	Av. Grain Separation in Tracks of Length					
	5	10	15	20	25	30
Alpha-Particles	1.61	1.65	1.69	1.72	1.74	
Deuterons	1.90	2.0	2.12	2.23	2.26	2.33
Protons	2.68	2.89	2.98	3.17		

[4] S. E. Sheppard, T. R. Wilkins, E. P. Wightman, and R. N. Wolfe, Kodak Research Lab. Comm. No. 590; J. Frank. Inst. **222**, 417–460 (1936).

[5] See also M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 266 (1937).

be approximately double that for alpha-particles. This ratio will be more exact for very fine grain emulsions where the increase in radius of action is able to bring an observable increased number of grains into the cone.

Observed values for alpha-particles and protons.—The data of Table VI are taken from Fig. 6 showing the average number of grains as a function of track length. These results are in good qualitative agreement with the predicted value of 2.0. For better quantitative agreement finer grained emulsions would be required, but unfortunately proton tracks are not secured when the grain size gets much smaller. It must be remembered, too, that photographic grains have fairly wide fluctuations in size and irregularity in position.

B. Comparison of proton and deuteron spacing

The values in Table VII are taken or calculated from Fig. 21 of Livingston and Bethe. From this it is seen that the ratio of proton to deuteron velocities does not change rapidly and can be taken as 1.25 in the range of our measurements.

Using the impulse equation as above

$$ee/\rho_p^2\cdot 1/V_p = ee/\rho_d^2\cdot 1/V_d$$

whence

$$\rho_d^2/\rho_p^2 = V_p/V_d = 1.25.$$

Since the number of grains is proportional to ρ^2, it follows that

$$n_d = 1.25 n_p$$

and this will also be the approximate value for the relative grain-spacings. Again it will be noted that the observed values are in good qualitative agreement with the calculated ones. The theory has predicted that deuteron spacing should lie between the spacings for alpha-particles and protons, and this is in accord with the observations.

TABLE VI. *Average number of grains as a function of track length for alpha-particle and deuteron tracks.*

Range in Emulsion	n_α	n_p	Observed n_α/n_p	Calculated n_α/n_p	Percent Difference
23.5μ	15	9	1.7	2.0	15
35	22	13	1.7		15
47	28	16	1.8		10
59	35	(19)	1.8		10

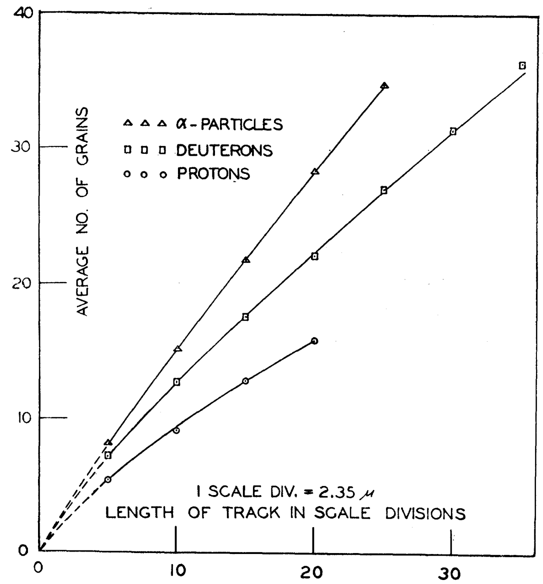


FIG. 6. Comparative spacing of alpha-, deuteron, and proton tracks.

Some examples of the use of the grain-spacing technique.—We have used grain-spacing in a number of cases to identify the nature of particles. For example, plates sent into the stratosphere were found to have numbers of very long tracks whose spacing showed them to be caused by alpha-rays presumably ejected in the emulsion by cosmic rays.[6] Fig. 7 shows a phe-

TABLE VII. *Ratio of proton and deuteron velocities at equal ranges.* (From Livingston and Bethe, reference 5, Fig. 21.)

Mean Range (Air)	Energy in Mev Protons	Energy in Mev Deuterons	V_p/V_d
2 cm	0.91	1.12	1.28
3	1.19	1.50	1.26
4	1.42	1.82	1.25
5	1.62	2.11	1.24
6	1.81	2.37	1.24

TABLE VIII. *Average number of grains as a function of track length for deuteron and proton tracks.* (*Calculated value of n_d/n_p 1.25.*)

Range in Emulsion	n_d	n_p	Observed n_d/n_p	Difference
23.5μ	13	9	1.4	11%
35	18	13	1.4	11%
47	22	16	1.4	11%
59	27	(19)	1.4	11%

[6] T. R. Wilkins, Nat. Geog. Soc. Stratosphere Series 2, 37 (1936); T. R. Wilkins and H. J. St. Helens, Phys. Rev. **51**, 1026 (1937).

nomenon first reported by us for plates sent up in balloons and especially in plates exposed for some months at the high altitude cosmic-ray station at Mt. Evans, Colorado, in 1936. Groups of tracks whose spacing shows them to be due to protons are seen to originate in a common point below the emulsion (in the glass or the binder). These groups are probably identical with those observed by Brode, MacPherson and Starr[7] in a cloud chamber. Similar tracks have more recently been found by M. Blau and H. Wambacher.[8]

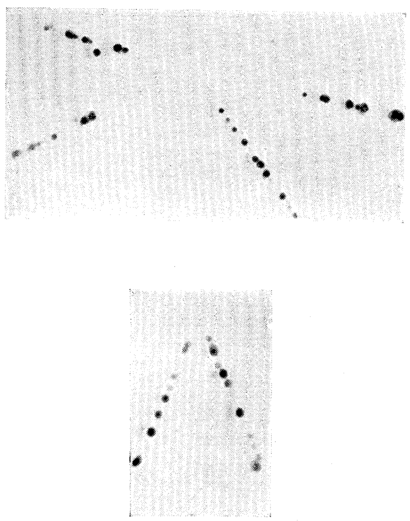


FIG. 7. Typical proton groups ejected by cosmic rays in plates exposed on Mt. Evans.

[7] R. B. Brode, H. G. MacPherson and M. A. Starr, Phys. Rev. **50**, 581 (1936).
[8] M. Blau and H. Wambacher, Nature **140**, 585 (1937).

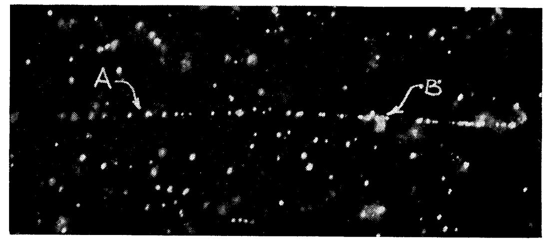


FIG. 8. A typical disintegration in a lithium impregnated emulsion exposed to neutrons. One track *B* has typical alpha-spacing; the other track *A* (only part of which is shown in the photograph) has greater spacing. (Mag. 900 diam.)

Many such groups have been found on our Mt. Evans plates. They have also been recently reported by Filippov, Gdanow and Gurevich.[9]

Figure 8 shows a typical disintegration of lithium (incorporated in a photographic emulsion) by neutron bombardment. The difference in the spacing of the alpha-particle track and the other (presumably H_3) is apparent.

In the case of tracks which do not lie flat in the emulsion, the correct grain spacing may be obtained by measuring the dip or by taking stereoscopic pictures. The theory for such ortho-stereoscopic photographs has been developed by Martin and Wilkins.[10]

Our thanks are due to Dr. J. M. Cork of the University of Michigan for his cooperation in the securing of the deuteron tracks and the neutron disintegrations.

[9] A. Filippov, A. Gdanow and I. Gurevich, C. R. Acad. Sci. USSR, **18**, 181 (1938).
[10] L. C. Martin and T. R. Wilkins, J. Opt. Soc. Am. **27**, 340 (1937).

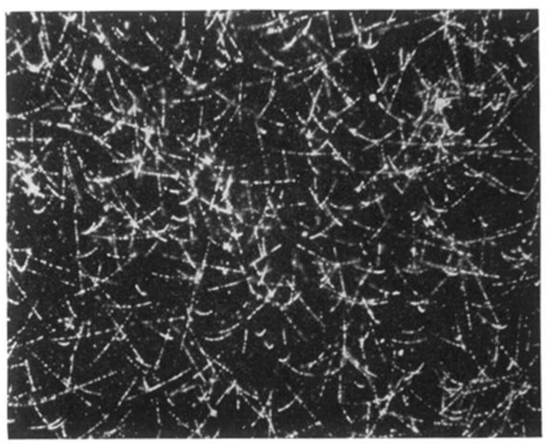
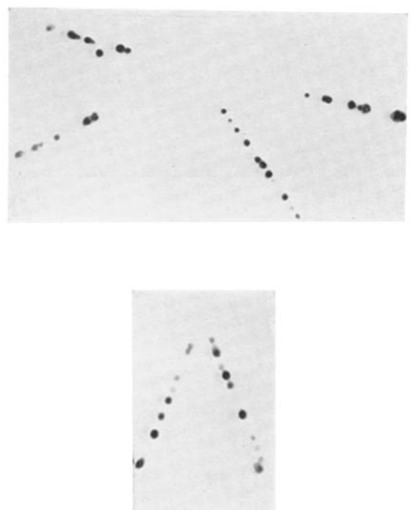


FIG. 1. ThC′ and ThC tracks in the Ilford R2 emulsion. (mag. 225 diam.)



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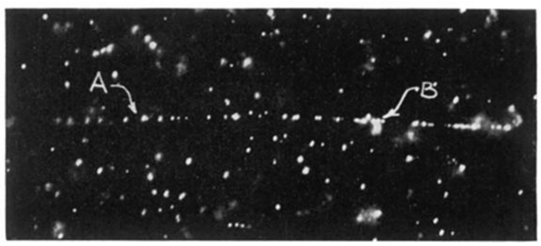

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