some of their isotope separation which, in the unperturbed case, would have been the same as that of $3s3p\ ^1P$ and would thus not have been observed.

It has been concluded that the observed structure cannot be due to mass effect alone, since, in that case, three components, nearly equally spaced, would be expected. It is also pointed out that the shift is in the wrong direction to be accounted for by a difference in nuclear fields caused by the fact that the isotopes with larger number of particles have larger radii. It is possible, and even probable, that the change in the fields in the neighborhood of nuclei is due to other causes, as well, and it is suggested that a survey of isotope displacements may yield valuable information in this connection.

The experimental work reported here was done in 1933 in the Physics Laboratory of the University of Michigan.

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The Scattering of Protons on Protons

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A technique for obtaining large numbers of high energy proton-tracks in hydrogen with a Wilson cloud chamber is described. The recoil-particles from cellophane bombarded by polonium alpha-particles were used as a source of protons. The velocity distribution of a sample of 500 protons is given. Over 15,000 stereoscopic views containing above 200,000 tracks of protons in a 90 percent hydrogen-10 percent air mixture have been obtained. Of the thirty-three intimate proton-proton collisions two were within the region of anomalous scattering of alpha-particles by hydrogen. The closest distance of approach realized experimentally was 6.1×10^{-13} cm.

Introduction

THE recent interpretations of Heisenberg[1] and others of the structure of the heavier nuclei as composed of protons and neutrons in close combination make any experimental evidence about the interaction of protons at close distances of primary importance. With the technique developed in the present experiments it is entirely possible to obtain more detailed experimental information of the laws governing proton-proton interaction. In view of the time that will be required to take and to analyze the large numbers of photographs necessary for conclusive evidence about the proton-proton interaction, it is felt appropriate to give an account of the methods used and the results obtained thus far. These results will serve to delineate the usefulness of a cloud chamber in attacking this problem and will thus be of value in any future work using either radioactive or high voltage sources of high energy particles.

For central and glancing collisions of alpha-particles on He and H nuclei, the following critical distances have been found within which the Coulomb interaction was no longer valid:[2]

	On He	On H
Central collisions	3.5×10^{-13} cm	4×10^{-13} cm
Glancing "	14.0×10^{-13} cm	8×10^{-13} cm

Taylor[3] was able to show, by assuming an interaction energy of the kind applied by Gamow[4] to the radioactive nuclei, that the main features of the earlier experiments could be accounted for without departure from the conception of a spherically symmetric field for an alpha-particle. In the above-mentioned experiments the failure of the Coulomb interaction might be ascribed either to the structure of the He nucleus alone or to both the He and the H nuclei. Further information on this point can be

[1] Heisenberg, Zeits. f. Physik **77**, 1 (1932); **78**, 156 (1932).

[2] Rutherford, Phil. Mag. **37**, 537 (1919); Chadwick and Bieler, Phil. Mag. **42**, 823 (1921); Rutherford and Chadwick, Phil. Mag. **4**, 605 (1927).

[3] Taylor, Proc. Roy. Soc. **A136**, 605 (1932).

[4] Gamow, *Atomic Nuclei and Radioactivity.*

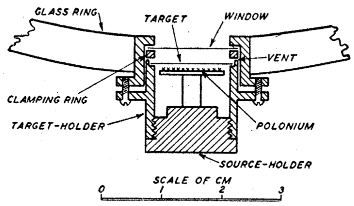


FIG. 1. Recoil proton-source.

obtained by determining the laws of scattering of protons by protons at close distances of approach.

The Wilson cloud-chamber offers a means of attacking this problem by using the type of high energy proton-source here described, since complete information can be obtained both as to angles and energies for each close collision.

Cloud Chamber and Recoil Proton-Source

The cloud chamber used was of the sylphon-bellows type, constructed from an earlier oil-sealed piston type. The chamber measured 18 cm internal diameter, 6 cm deep with water used for the floor of the chamber to give adjustable depth. The chamber proved to be very dependable in operation, the expansion ratio was not changed and the chamber remained sealed throughout the time required to photograph over 15,000 expansions.

The recoil-proton source as finally developed is shown in Fig. 1. In order to avoid contamination by recoil aggregates, the interior of the chamber was separated from the proton-source by a thin aluminum window. A cellophane target bombarded by polonium alpha-particles was used as a convenient source of protons. At the place marked "vent" several small channels were cut in the rim of the target holder to allow free access of air to the space between the target and the window. This was necessary to avoid contamination from the brittle bombarded cellophane in case a break should develop in the aluminum window. The cellophane and the aluminum foil each had 3.5 cm air-equivalent stopping power for alpha-particles. The polonium source was of approximately 10 millicuries, prepared by Dr. Hafstad from radon tubes secured from Dr. J. A. Bearden and supplied through the courtesy of Dr. C. F. Burnam and Dr. F. West of the Kelly Hospital, Baltimore.

Fig. 2 shows a stereoscopic pair of photographs of a typical expansion. As can be seen, there were always a few old diffused tracks present. This was due to the type of shutter found to be necessary. A magnetically operated shutter between the target and the window, so reduced the solid angle of the beam that only a few proton-tracks appeared per expansion. However, it was found that a vertical plate, attached to the floor of the chamber and covering the window only when the chamber was compressed, proved to be a better compromise than reduction in the number of tracks.

Fig. 3 shows the velocity distribution of a sample of 500 proton-tracks obtained in successive expansions. The apparent rapid decline in the number of protons as the velocity falls below 10^9 cm sec.$^{-1}$ was due to the experimental impossibility of obtaining many resolved tracks in the immediate vicinity of the source. The method of obtaining the reduced range in air with the corresponding velocity is described in the next section.

In the upper right-hand corner of Fig. 2 the range-gauge can be seen. This consisted of a thin nickel wire with a weak source of polonium deposited on the tip. This source was of strength sufficient to give one alpha-particle every few expansions. The shutter for this source consisted of a hollow tube attached to the floor of the chamber, with an opening in one side which determined a conveniently small solid angle for the alpha-particle. Such a shutter was found to be necessary, since only a few old tracks from a source without a shutter were sufficient to obscure any clear track formation in that half of the chamber.

Results of Close Collisions of Protons

Blackett and Lees[5] have obtained the experimental curve relating reduced air range of protons with the corresponding velocity. Following their results this reduced air range was obtained from the measured proton ranges in the 90 percent hydrogen-10 percent air mixture used in the chamber

For this conversion to the reduced air-range, the range of a standard alpha-particle in the

[5] Blackett and Lees, Proc. Roy. Soc. **A134**, 665 (1932).

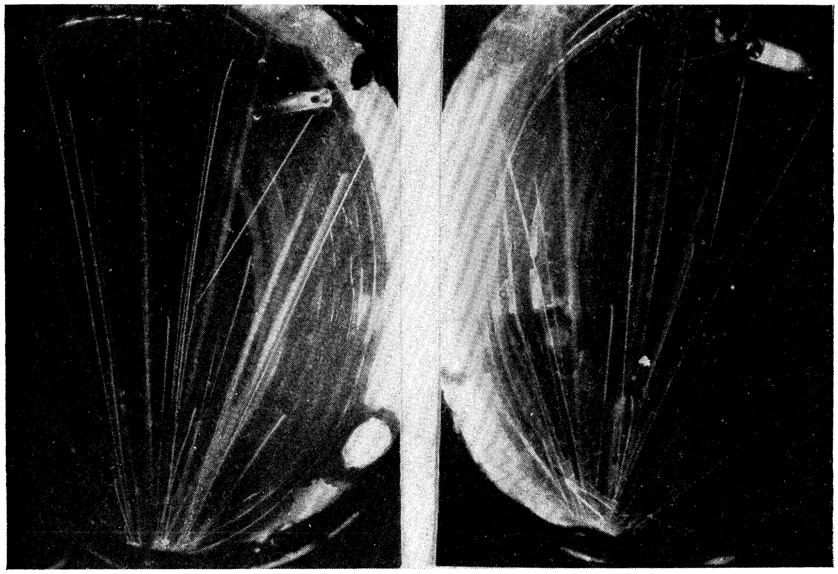


FIG. 2. Stereoscopic pair of photographs of a typical expansion.

same mixture must be known. This was obtained by reprojection of the alpha-particle tracks from the range-gauge described above. In practice it was found that the ranges of the longest tracks clustered closely about a mean; thus giving a good value for the polonium alpha-particle range in the particular gas mixture used.

From the photographs collisions of protons with protons could be distinguished from collisions with heavier atoms by the following criteria: (1) The angle between the nuclei departing from the collision must have been ninety degrees, (2) the angle the longer spur made with the initial direction could not be greater than forty-five degrees, (3) neither of the spurs could have a component antiparallel to the direction of the incident proton.

If in a collision V and R were the velocity and residual reduced range of the incident particles, V_ϕ and R_ϕ the corresponding quantities for the

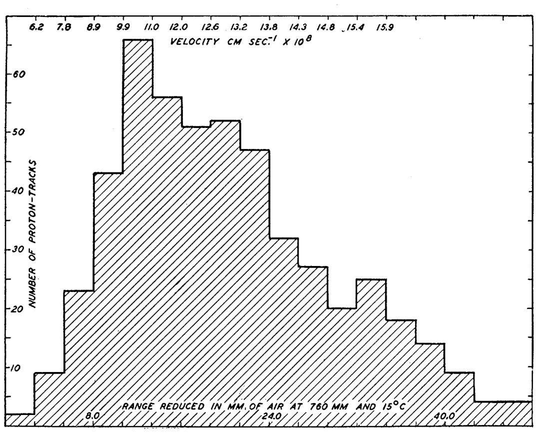


FIG. 3. Velocity-distribution of a sample of 500 proton-tracks.

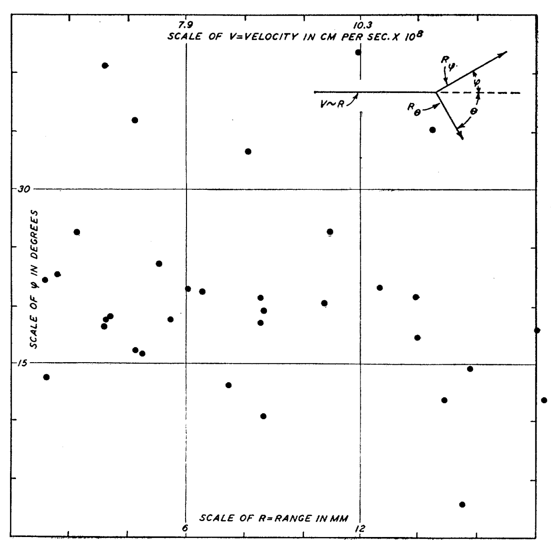


FIG. 4. Scatter diagram of the 33 intimate proton-proton collisions.

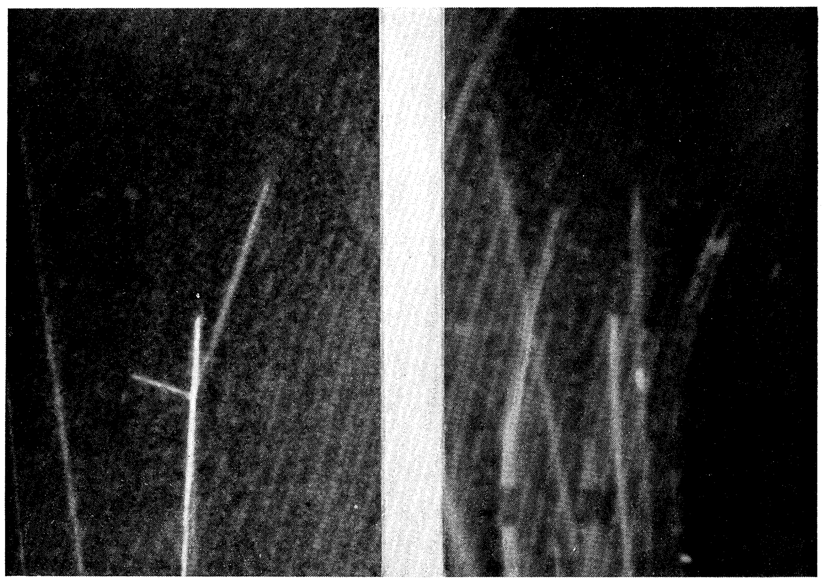


FIG. 5. A proton-proton collision of high energy-exchange, the longer spur being of 3-cm length in the chamber; the plane of the collision contains the axis of one of the camera lenses.

longer spur making an angle ϕ with the initial direction, V_θ, R_θ and θ those for the shorter spur, then the values of V_ϕ and V_θ were sufficient to determine the value of V provided energy was conserved in the collision. In all of the proton-proton collisions observed the collision was coplanar within the accuracy of measurement. From the measured lengths of the spurs of a collision the values of R_ϕ and R_θ as reduced air-ranges were computed following the method of Blackett and Lees. From their curve the values of V_ϕ and V_θ were obtained, and assuming conservation of energy it follows that,

$$V^2 = V_\phi^2 + V_\theta^2.$$

From this value of V the corresponding value of R was then obtained as outlined above.

In a collision of two identical particles it is clearly impossible to distinguish between the incident and the recoil-particles after the collision. Thus there are two possible values of the energy-exchange in a collision which give experimentally similar results. Hence for the interpretation of the present results it was adopted as a convention that after the collision the incident particle retained the major fraction of its energy.

In Fig. 4 the values of ϕ and V are shown for the thirty-three collisions of proton on proton obtained in this series of photographs. It can be seen from this distribution that no large deviations accrued from what would have been expected theoretically.

The distribution diagram gives a better idea of what was undoubtedly the actual distribution of scattered particles if one blocks out the cells between $R=0$ to 12 mm, and $\phi=0°$ to 15°. In the analysis of the photographs collisions were rejected as not surely those of protons on protons if one of the spurs was too short to determine $\phi+\theta=90°$ within a reasonable degree of accuracy. Since these rejected collisions were those of small energy-exchange, hence of small ϕ as well as of small V, it is seen that the three lower left-hand cells were deprived of population by the experimental method necessary in the analysis. The data obtained were not sufficient to justify a quantitative comparison of the population of the cells in the diagram with the numbers to be expected theoretically.

The distance of closest approach of the two colliding particles on the assumption of Coulomb interaction was computed from the formula

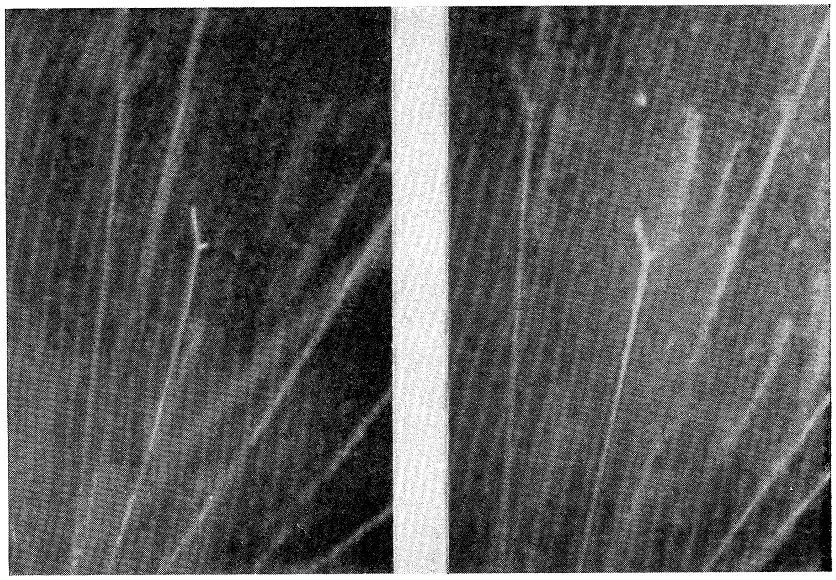


FIG. 6. A proton-proton collision of low energy-exchange lying nearly in a horizontal plane, the longer spur being of 5-mm length in the chamber.

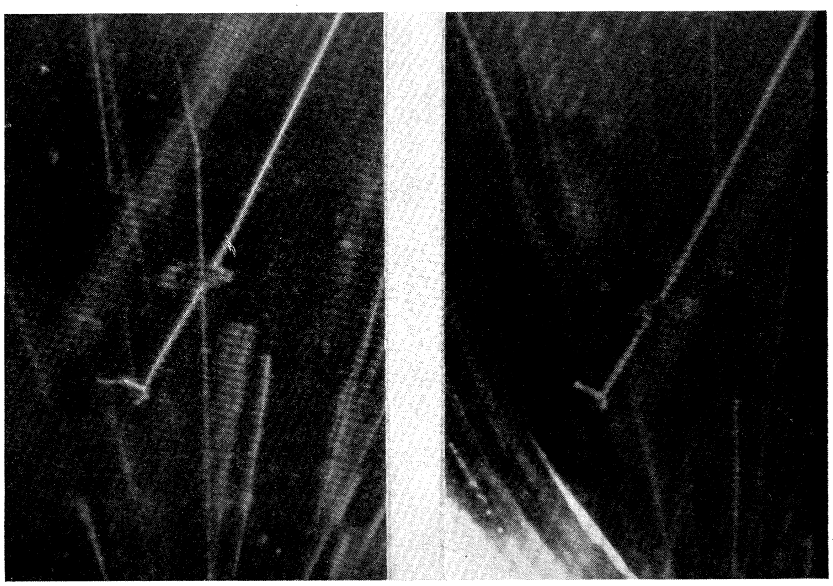


FIG. 7. An alpha-particle from the range gauge source shown because of its unusual career. The effect of displaced tracks is shown when the alpha-particle passed through the region previously traversed by a proton. The track found by the expansion appears to go both above and below the proton track. At the end of the track the alpha-particle made a close collision with a light atom, one of the recoiling particles then made another collision with large angle of deviation, the other recoil particle making two successive large angle deflections.

given by Darwin.[6] In the present case this becomes

$$D=(2e^2/v^2m)(1+\csc\phi)$$

where e and m are the charge and mass of the proton and ϕ is the angle the particle having the major fraction of the energy after the collision makes with the direction of the incident particle, and V is the velocity of the incident particle at the instant of the collision.

That some of the recorded collisions were within the region of anomalous scattering of alpha-particles on hydrogen can be seen from Table I.

The efficiency of the cloud chamber in obtaining information concerning close proton collisions is indicated by the distribution of the thirty-three collisions suitable for measurement given in Table II.

TABLE I. *The distances of closest approach realized in the ten most intimate collisions.*

V ($\times 10^8$ cm sec.$^{-1}$)	ϕ	D ($\times 10^{-13}$ cm)
11.09	35.0°	6.1
10.28	41.7	6.5
12.04	17.9	8.1
10.92	20.7	8.8
10.02	26.4	8.9
10.57	21.6	9.1
8.84	33.1	9.9
10.96	17.3	10.0
9.94	20.1	10.9
12.09	12.0	10.9

[6] Darwin, Phil. Mag. **27**, 499 (1914).

TABLE II.

Limits of D	No. occurring	Limits of D	No. occurring
0 to 5×10^{-13} cm	0	50 to 60×10^{-13} cm	0
5 to 10	8	60 to 70	2
10 to 20	11	70 to 80	0
20 to 30	8	80 to 90	1
30 to 40	0	90 to 100	1
40 to 50	2		

In eight of the thirty-three collisions, from a total of over 200,000 tracks of protons in hydrogen, the distance of closest approach was less than 10×10^{-13} cm. Of these eight, two were within the region of anomalous scattering observed by Rutherford, Chadwick and Bieler in their experiments.

Figs. 5, 6 and 7 show further interesting examples of the original photographs obtained by this method.

The author wishes to express his appreciation of the assistance and encouragement of Professor J. A. Bearden of the Johns Hopkins University under whose immediate direction this work was done, and of Dr. J. A. Fleming, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and of members of the staff of that Department, where the experimental work was carried out.

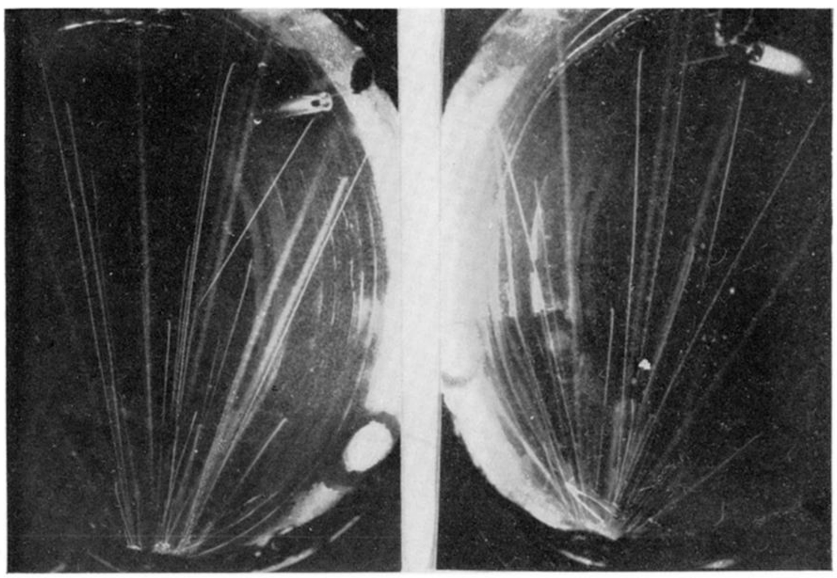


FIG. 2. Stereoscopic pair of photographs of a typical expansion.

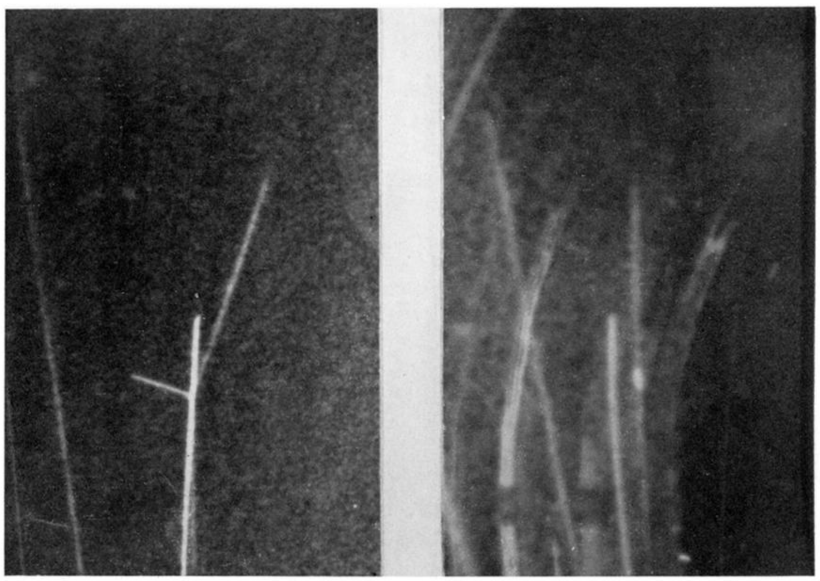


FIG. 5. A proton-proton collision of high-energy-exchange, the longer spur being of 3-cm length in the chamber; the plane of the collision contains the axis of one of the camera lenses.

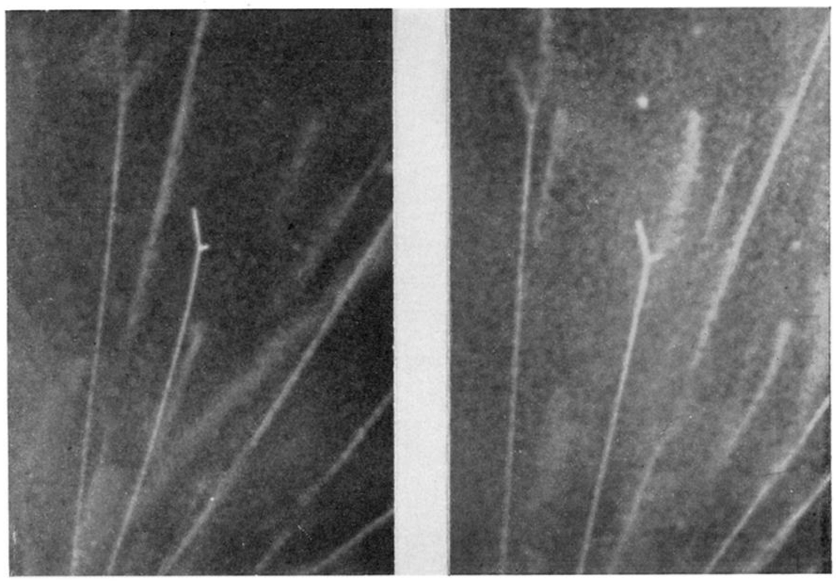
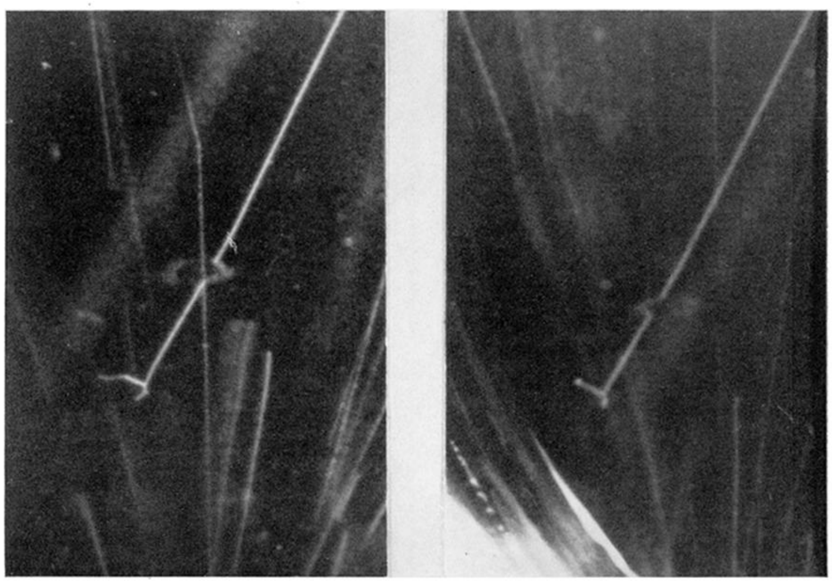


FIG. 6. A proton-proton collision of low energy-exchange lying nearly in a horizontal plane, the longer spur being of 5-mm length in the chamber.



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