THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 71, NO. 5 MARCH 1, 1947

Cloud-Chamber Studies of Electronic and Nuclear Stopping of Fission Fragments in Different Gases

J. K. BØGGILD, O. H. ARRØE, AND T. SIGURGEIRSSON
Institute for Theoretical Physics, University, Copenhagen, Denmark

(Received November 16, 1946)

The range of fission fragments in different gases has been studied by means of the cloud-chamber method. The reduced range was found to increase from xenon to helium, and the range in helium was found to be about 18 percent larger than in argon, which is in agreement with previous determinations. The reduced range in hydrogen was found to be smaller than in other gases, pointing to a comparatively larger electronic stopping effect. The reduced ranges of fragments passing through hydrogen and deuterium, respectively, have been compared and the range in deuterium was found to be about 6 percent larger than that in hydrogen. Since the electronic stopping effect is identical in both gases, the difference in the ranges must be ascribed to the nuclear stopping effect. The spread of the range within the groups was discussed in relation to the energy measurements by Flammersfeld, Jensen, and Gentner, using Bohr's theory of the stopping effect, and a reasonable agreement was obtained. The previous conclusions concerning the velocity-range relations of fission fragments were confirmed by new, more direct evidence, using close collisions for a determination of the velocity or mass of the fragments.

As reported in a previous paper,[1] the ratio between the range of fission fragments and the range of α-rays in helium was found to be about 20 percent larger than the corresponding ratio in argon. As pointed out by Bohr,[2] this difference is just in agreement with the different shapes of the velocity-range curves in light and in heavy gases to be expected from theoretical considerations concerning the electronic and nuclear stopping effects. A closer examination[3] of the range-velocity relation of fission fragments in helium and a comparison with the corresponding relation in argon has, within the experimental errors, confirmed the theoretical considerations and indicates that the rate of velocity loss is similar in the two gases in the first part of the range, where the stopping is caused mainly by electronic encounters, whereas the end part of the velocity-range curve in helium is comparatively longer than that in argon, corresponding to the effect of the smaller energy loss by nuclear collisions in helium. In view of the theoretical interest in the stopping effect of still lighter or heavier gases, an examination of a large number of paired fragment tracks in hydrogen, deuterium, and xenon was performed and, at the same time, the former range measurements in helium and in argon were repeated in order to obtain more exact statistical data.

EXPERIMENTAL METHOD

The technical arrangement was the same as in the previous investigations, except for a few

[1] J. K. Bøggild, K. J. Brostrøm, and T. Lauritsen, Phys. Rev. 59, 275 (1941).
[2] N. Bohr, Phys. Rev. 59, 270 (1941).
[3] J. K. Bøggild, Phys. Rev. 60, 827 (1940).

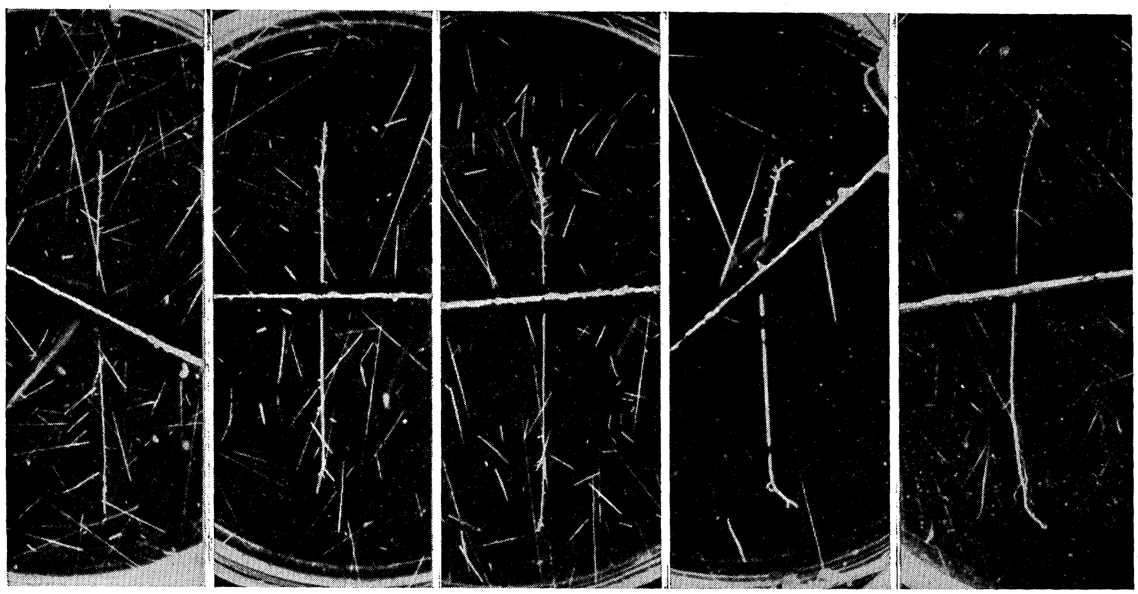


FIG. 1. Paired fragment tracks in (a) hydrogen, (b) deuterium, (c) helium, (d) argon, (e) xenon.

improvements. A 15-cm cloud chamber was used and, in order to reduce the stopping power of the vapor as much as possible, water was used as drop producing agent instead of alcohol-water mixtures. To avoid condensation of vapor on the uranium foils, 5 percent of NaCl was dissolved in the water gelatines. The stopping power of the gas mixtures was controlled by means of Po-α-particles from a source placed inside the chamber. The uranium layers were evaporated on $\frac{1}{2}\mu$-aluminum foils and, in the case of xenon investigations, on a mica foil. The thickness of the uranium layers was about 0.4 to 0.6 mg/cm^2. For the calculation of the stopping power of the foils, 1.0 cm of air was taken equal to 1.5, 1.6, and 4.0 mg/cm^2 for mica, aluminum, and uranium, respectively.

The tracks of fission fragments were thoroughly examined and only those paired tracks were used for range determinations, where the end points of both tracks were distinctly visible on the photographs. The end of the range, especially in light gases, is uniformly characterized by a tuft consisting of several short branches. Figure 1 demonstrates a few typical cases of paired fragment tracks in hydrogen, deuterium, helium, argon, and xenon. Besides the typical characteristics of fission fragment tracks already described in previous papers[4] (heavy ionization, ejection of side branches, and fortuitous bending), slight differences appear in the extreme light and in heavy gases. As was to be expected from theory, the tracks in hydrogen and deuterium, as a rule, are rather straight from the start until pretty near the end of the range, whereas the tracks in argon and especially in xenon, due to numerous small collisions with heavy atoms, are submitted to a considerable bending over the greater part of the range. Also the length and the number of side branches are seen to change considerably with the gas in the chamber. In hydrogen, deuterium, and helium the tracks exhibit numerous branches; in argon, however, the branches usually are very short, and in xenon they are practically reduced to small lumps on the stem. Closer collisions which occur not infrequently in all gases and result in branches of considerable length are suitable for velocity determinations and will be discussed below.

COMPARISON OF RANGES

The results of measurements of the reduced ranges* are given in the histograms of Fig. 2,

[4] J. K. Bøggild, K. J. Brostrøm and T. Lauritsen, Kgl. Danske Vid. Sels. Math.-fys. Medd. **18**, No. 4 (1940).

* The reduced range r_F is calculated according to the formula $r_F = 38.0r/r_\alpha$ mm, where r is the measured range of

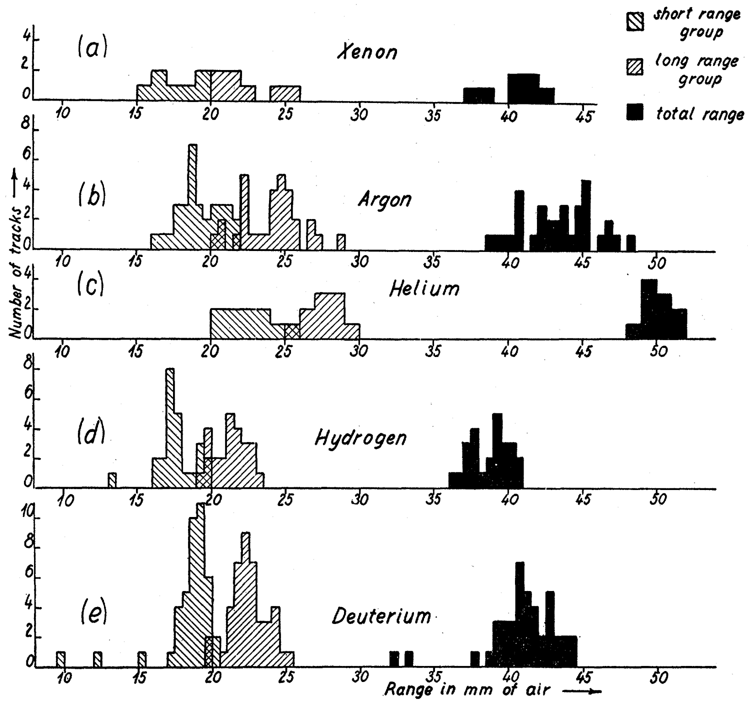


FIG. 2. Range distribution in different gases.

where the groups of short and long range are drawn with opposite cross-hatching. The number of fission tracks in xenon and in helium is rather small, and the corresponding histograms reproduce the numbers of tracks in range intervals of 1 mm, whereas intervals of 0.5 mm are chosen in the other cases, where the statistical material is somewhat more copious. In hydrogen and deuterium, a few cases of very short range particles were found. A comparison with other investigations suggests, however, that these very short range tracks originate in some accidental source of error as, for instance, the presence of water droplets; consequently, these tracks were not included in the statistics. The mean reduced range in mm of the two groups and the mean total range are given in Table I together with the previous determinations of the mean ranges in helium and argon.

TABLE I. Ranges in mm of air.

Gas	Short range group	Long range group	Total range
Xenon	18	23	41
Argon (previous data)	19	25	44
Argon	19.4	23.9	43.3
Helium (previous data)	23	30	53
Helium	23	28	51
Hydrogen	17.7	21.1	38.8
Deuterium	18.9	22.5	41.4

the tracks and r_α the range of the α-particles from the control study. The constant 38.0 corresponds to the range of Po-α-particles at normal pressure and 15°C.

Though the determination of the mean range is not too precise, the number of fission tracks being not very large, the values in Table I indicate characteristic differences in reduced ranges for the various stopping materials. If, in the first instance, we assume the electronic stopping power for fission fragments and α-particles to depend in approximately the same manner on the atomic number of the gas, these differences must evidently be ascribed to the effect of nuclear collisions. The fact that nuclear collisions in the case of fission fragments, in contrast to the case of fast α-particles, actually have a considerable influence on the range is perhaps most clearly demonstrated by the results obtained in H and D. In these two gases, the electronic stopping must, of course, be identical, and the difference in the ranges gives a measure of the importance of nuclear stopping. It may be added that the longer range in D is just what was to be expected, since, the H and D nuclei having the same charge, the lighter nuclei will receive more energy in corresponding collisions, except for the close collisions which are rare and unimportant for the mean stopping effect.

In order to test in somewhat more detail the agreement with theory,[2] we note that the nuclear stopping power must be expected to be very nearly proportional to Z_2^2/M_2, M_2 and Z_2 being the mass and charge of the nuclei of the atoms of the gas, and under the assumption that the dependence of the electronic stopping power on Z_2 may be taken from that of α-particles, we may therefore estimate the relative importance of the nuclear stopping in the various substances. This quantity should be directly connected with the reduced range. Thus, the reduced range is expected to decrease with increasing ratio between nuclear and electronic stopping power. If, to a first approximation, we put the electronic stopping power proportional to $Z_2^{\frac{1}{2}}$, the ratio of nuclear to electronic stopping, for heavier substances for which $M_2 \sim 2Z_2$, is seen to increase roughly as $Z_2^{\frac{1}{2}}$. We should, therefore, expect the reduced range to decrease with increasing Z_2 just corresponding to the experimental results in He, A, and Xe.

It is obvious, however, that the marked shortness of the reduced range in H and D compared with He is not compatible with the above assumptions concerning the electronic stopping power. In fact, even if on account of the large value of Z_2/M_2 in H, these assumptions lead to a reduced range in H somewhat shorter than in He, it should still be longer than in Xe and, in particular, the reduced range in D should be expected to be even longer than in He. The measurements, therefore, seem to indicate a comparatively large electronic stopping power in H and D, pointing to an abnormally high effective charge of the fragments. It is of interest, however, that this feature is just in accordance with theoretical considerations suggesting a much smaller probability of electron capture by the fragments in hydrogen than in other gases.

A point which may require further discussion is the rather small difference between the reduced ranges in H and D, compared with the difference between the ranges in Xe and He. In fact, in D the relative importance of nuclear stopping is only half that in H, just as in He it is only about half that in Xe. A possible explanation would seem to be that, on account of the relatively large electronic stopping power, the nuclear stopping in H and D becomes of importance only for smaller fragment velocities than in other gases, in which case variations in the nuclear stopping would have a correspondingly smaller effect on the ranges. A more general discussion of these and other problems concerning the stopping of heavy nuclei will appear in a forthcoming paper by Bohr.[5]

Extremely valuable information concerning the mechanism of uranium fission was given by Flammersfeld, Jensen, and Gentner,[6] and a comparison with our range analysis might be of some interest. Unfortunately, however, the possibility of a thorough analysis by means of the cloud-chamber method is rather limited in view of the paucity of statistical material, the finite thickness of the uranium layer, and a probably rather large range straggling. According to the theory,[2] the straggling of fission fragments is practically only due to the nuclear collisions, and the relative straggling is expected to be considerably larger in heavy than in light gases and smallest in hydrogen. Since the breadth of the range groups appears to be approximately the same in heavy and in light gases, it seems rather reasonable to attribute the main part of the spread in range to fluctuations in the initial velocity, charge, and mass of the fragments in the fission process.

A comparison of the breadth of the range groups with the fluctuation in energy reported by Flammersfeld *et al.* indicates that the range is less affected by variations in the fission process than is the energy of the fragments. This is just what should be expected from theoretical considerations. The appropriate formula given by Bohr[2]

$$R = \text{const. } M_1 \cdot Z_1^{-\frac{2}{3}} \cdot V,$$

where R is the range, M_1 and Z_1 the mass and nuclear charge of the fragment, and V the velocity, leads to the following equation, when

[5] N. Bohr, Kgl. Danske Vid. Sels. Math.-fys. Medd. in press.

[6] A. Flammersfeld, P. Jensen, and W. Gentner, Zeits. f. Physik **120**, 450 (1943).

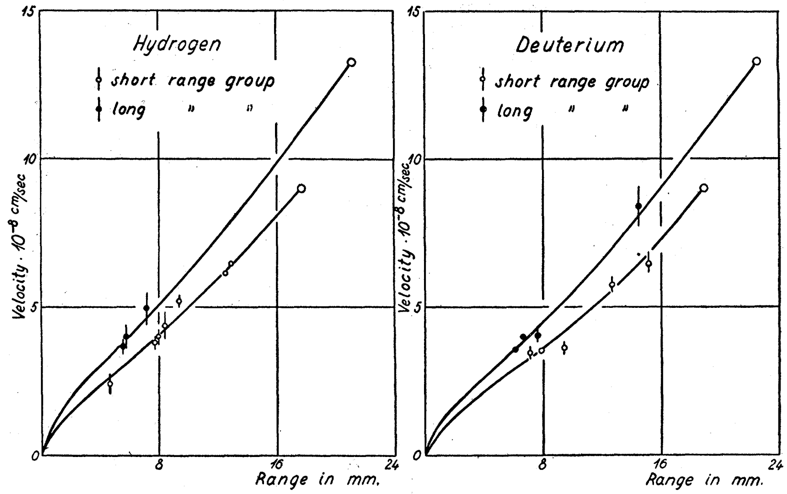


FIG. 3. Velocity-range relations in hydrogen and deuterium.

Z_1 is assumed to be proportional to M_1,

$$R = \text{const.} \cdot M_1^{-1/6} \cdot E^{1/2},$$

where E is the energy. Since $M_1^{-1/6}$ is nearly constant for the fragments in the same group, the spread in range is roughly equal to half the spread in energy.

VELOCITY-RANGE DETERMINATION FROM LARGE BRANCHES

From quite general arguments regarding the dependence of stopping power on the charge, mass, and velocity of the incident particle, it appears evident that the heavy fragment group corresponds to the short range group, and the light fragment group to the long range group.[7] Still, the verification of this assumption in previous experiments was based mainly on a statistical evaluation of the distribution of branches produced by close collisions with gas atoms,[8] whereas velocity determinations from individual large branches only gave a mean velocity range curve common to the two groups.

As mentioned above, some of the fragment tracks in this work appear with individual large branches suitable for velocity determination and, consequently, it is possible to produce separate velocity-range curves for the two groups of fragments. Because of the fact that the fragment tracks are comparatively straight in hydrogen and deuterium gas, the accuracy of the measurements of the angle between the direction of the branch is better here than in other gases. The velocity examination is, therefore, limited to close collisions with protons and deuterons. The velocity v of a fragment after a collision is given by the formula

$$v = u\left(\frac{(1+k)^2}{4\cos^2\theta} - k\right)^{\frac{1}{2}},$$

where k is the ratio of the masses of the gas nucleus and the fragment, u is the velocity of the gas nucleus, and θ the angle between the direction of the stem before the collision and the direction of the branch. By collisions with protons and deuterons the ratio k is rather small and the following approximation can be used:

$$v = u/2\cos\theta.$$

The range of the branches was reduced to normal air conditions by means of the values for the stopping power of hydrogen relative to air, given by Gurney.[9] The velocity u for protons was obtained by means of the velocity-range relation for protons, given by Blackett and Lees,[10] with the velocity increased by 5 percent,[11] and for deuterons the velocity-range relation was found

[7] The opposite adaptation of range groups is, without reference, mentioned by Fluegge; J. Mattauch (and S. Fluegge), *Kernphysikalische Tabellen* (Verlagsbuchhandlung, Julius Springer, Berlin, 1942).

[8] N. Bohr, J. K. Bøggild, K. J. Brostrøm, and T. Lauritsen, Phys. Rev. **58**, 839 (1940).

[9] R. W. Gurney, Proc. Roy. Soc. **A107**, 340 (1925).

[10] P. M. S. Blackett and Lees, Proc. Roy. Soc. **A134**, 658 (1931).

[11] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, §95 (1937).

FIG. 4. Paired fragment tracks in hydrogen. The up-going fragment track appears with two long proton branches, one close after the other, both suitable for velocity determination.

from the proton relation by a doubling of the abscissa.

Figure 3 shows the result of ten individual velocity determinations in hydrogen and nine in deuterium. A rough estimation of the errors in the velocity determination due to the inaccuracy in the measurement of the angles and of the branch lengths is indicated by vertical lines through the points. The most probable initial velocities are calculated by means of the data given by Flammersfeld *et al.*; the values obtained are 9.0×10^8 and 13.3×10^8 cm/sec. for the heavy and the light fragment groups, respectively. Assuming the low initial velocity to correspond to the short range group, the velocity-range curves in both gases turn out to be rather reasonable and consistent with the previous results, whereas it seems to be quite impossible to produce reasonable relations if the low initial velocity were attributed to the long range group. Determinations of the velocity have not been carried out close to the end of the range, since the branches here are very short and, thus, such determinations would lead to considerable inaccuracy. Two very close collisions with protons, leading to extremely long branches, provide especially valuable velocity determinations rather early in the range of the short range group. The two branches in question are produced one close after the other by the same fragment, and a reproduction of the tracks is given in Fig. 4.

Further argument to attribute the short range group to the heavy particle group is produced by a picture of the tracks of a close collision between a fission fragment and an argon nucleus, reproduced in Fig. 5. The down-going track has a range of 18.6 mm and the up-going track, in spite of the collision, a range of 22.1 mm. Therefore, the up-going track undoubtedly belongs to the long range group. The angles φ and θ* are found to be 22° and 45°, respectively, and the mass M_F of this fragment can be calculated by means of the formula

$$\frac{M_A}{M_F}=\frac{\sin\varphi}{\sin(2\theta+\varphi)}.$$

Since the mass of the great majority of argon atoms is 40, the mass of the fragment in question

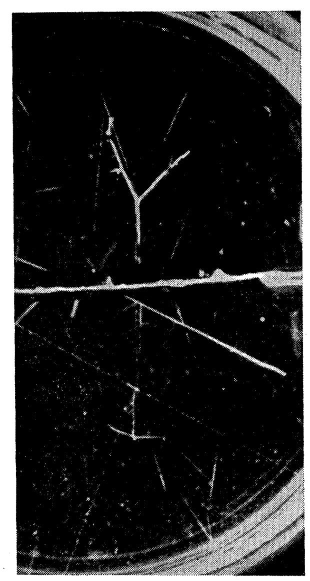


FIG. 5. Paired fragment tracks in argon. The down-going fragment track is cut over by an almost parallel proton track, but the end point of the fragment tracks is clearly visible. The up-going long range fragment collides with an argon nucleus, and the mass of the fragment is found to be about 100 mass units. Hence, this long range fragment evidently belongs to the light fragment group.

* φ is the angle of deflection of the fragment and θ the angle between the direction of the argon branch and the direction of the stem before the collision.

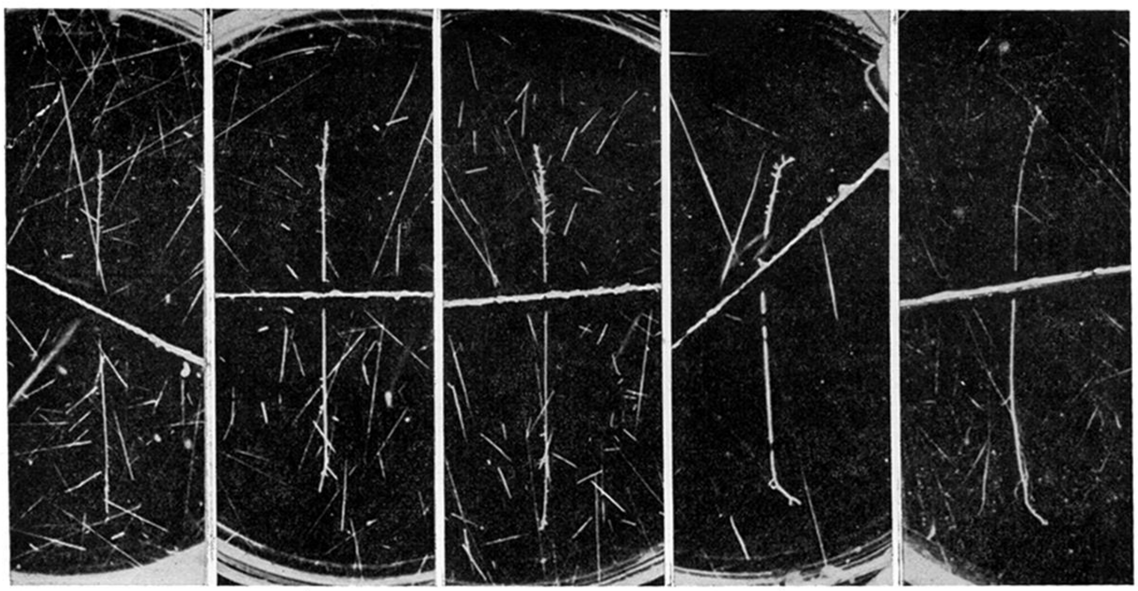
is found to be 100 ± 5 and, hence, this long range fragment evidently belongs to the light fragment group.

Obviously, the above examination of individual large branches leads to velocity-range relations in conformity with previous, more indirectly produced information.

Some recent experiments by Lassen[12] have given important information concerning the charge, energy, and energy loss of fission fragments passing through matter. In broad outline, Lassen's experiments are in agreement with the cloud-chamber studies from this Institute; intimate conformity in all details is, however, not to be expected in view of the fact that close collisions take place chiefly in the later part of the range, whereas the accuracy of Lassen's experiments is better in earlier parts of the range.

The main part of the work described in the present paper was already carried out in 1943, but the completion and publication were delayed by wartime conditions. The authors wish to express their thanks to Professor Niels Bohr for his interest and advice regarding the experiments and their discussion. We are also indebted to the Norwegian Hydro-electrical Company which placed the xenon gas at our disposal and to Director S. Madsen, Copenhagen, for supplying us the argon gas.

[12] N. O. Lassen, Kgl. Danske Vid. Sels. Math.-fys. Medd. **23**, No. 2 (1945); Phys. Rev. **68**, 142 (1945); Phys. Rev. **69**, 137 (1946); Phys. Rev. **70**, 577 (1946).



a b c d e

FIG. 1. Paired fragment tracks in (a) hydrogen, (b) deuterium, (c) helium, (d) argon, (e) xenon.

FIG. 4. Paired fragment tracks in hydrogen. The up-going fragment track appears with two long proton branches, one close after the other, both suitable for velocity determination.

FIG. 5. Paired fragment tracks in argon. The down-going fragment track is cut over by an almost parallel proton track, but the end point of the fragment tracks is clearly visible. The up-going long range fragment collides with an argon nucleus, and the mass of the fragment is found to be about 100 mass units. Hence, this long range fragment evidently belongs to the light fragment group.