# Range-Velocity Relation for Fission Fragments in Helium

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The range-velocity relation of fission fragment tracks in helium has been studied by means of individual close collisions as well as by statistical considerations of the branch frequency. The comparison with previous investigations of fragment tracks in argon indicates that the shape of the range-velocity curves for the two gases differs appreciably in the last part of the range just as was to be expected from theoretical considerations concerning the relative contributions to the stopping power by electron encounters and nuclear collisions in light and heavy gases.

AS reported in previous papers,[1] cloud-chamber tracks of fission fragments in argon as well as in helium have been obtained in this Institute. While the tracks in argon offered sufficient material for a detailed study of the range-velocity relation, the tracks in helium were so far mainly used for range measurements. The ratio between the range of the fission fragments and the range of $\alpha$-rays was in helium found to be about 20 percent larger than the corresponding ratio in argon. As pointed out by Professor Bohr, this difference is just in agreement with the different shape of the range-velocity curves in light and in heavy gases to be expected from theoretical considerations.[2]

In fact, the range-velocity curve consists of an almost linear slope extending over the larger part of the range, and an end part, where the rate of velocity loss to begin with decreases and, after passing through a minimum, rapidly increases corresponding to a steep descent of the curve at the very end of the range. The stopping in the first part is due almost entirely to electronic encounters, whereas the stopping in the later part is mainly caused by nuclear collisions, the effect of which becomes preponderant when the total charge of the fragment is nearly neutralized by electron capture. While the electronic stopping effect in different gases is proportional to the stopping power for $\alpha$-rays of the same velocity, the nuclear stopping effect increases far more rapidly with the atomic number of the gas. This means that the end part of the range should be relatively longer in a light gas than in a heavy one, and in helium it was estimated to be three times as long as in argon. Since in this gas the end part is roughly 10 percent of the range, it should be about 30 percent in helium, and the whole range in helium relative to $\alpha$-rays ought therefore to be just about 20 percent longer than in argon.

In view of the theoretical interest of a closer examination of this question the experiments were continued, and a large number of cloud-chamber pictures of fission fragment tracks in helium have recently been obtained which allow a direct investigation of the range-velocity curve in this gas. A few typical examples of such pictures are given in Fig. 1 where, for comparison, one of the older photographs in argon is also shown. As seen, the tracks in helium are less curved than in argon, as was to be expected from theory,[3] since the mean deviation over a part of the range with a given velocity loss should be proportional to the square root of the atomic number; furthermore, the number of branches of a given length is considerably greater in helium due to the larger range of recoil particles of the same energy in helium than in argon.

The previous papers contain a discussion of two different ways of velocity determination, *viz.*, the usual direct method by means of individual close collisions, and a statistical method based on an examination of the branch frequency along the range. The first method has the advantage of giving absolute values but the reliability of the velocity determination depends upon the certainty of the identification of the particles

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[1] K. J. Brostrøm, J. K. Bøggild, and T. Lauritsen, Phys. Rev. 58, 651 (1940); N. Bohr, J. K. Bøggild, K. J. Brostrøm, and T. Lauritsen, Phys. Rev. 58, 839 (1940); J. K. Bøggild, K. J. Brostrøm, and T. Lauritsen, Phys. Rev. 59, 275 (1941); J. K. Bøggild, K. J. Brostrøm, and T. Lauritsen, D. Kgl. Danske Vid. Selsk. Math.-fys. Medd. (Math.-phys. Comm., Acad. Sci. Copenhagen) 18, (1940).

[2] N. Bohr, Phys. Rev. 59, 270 (1941).

[3] N. Bohr, Phys. Rev. 58, 654 (1940).

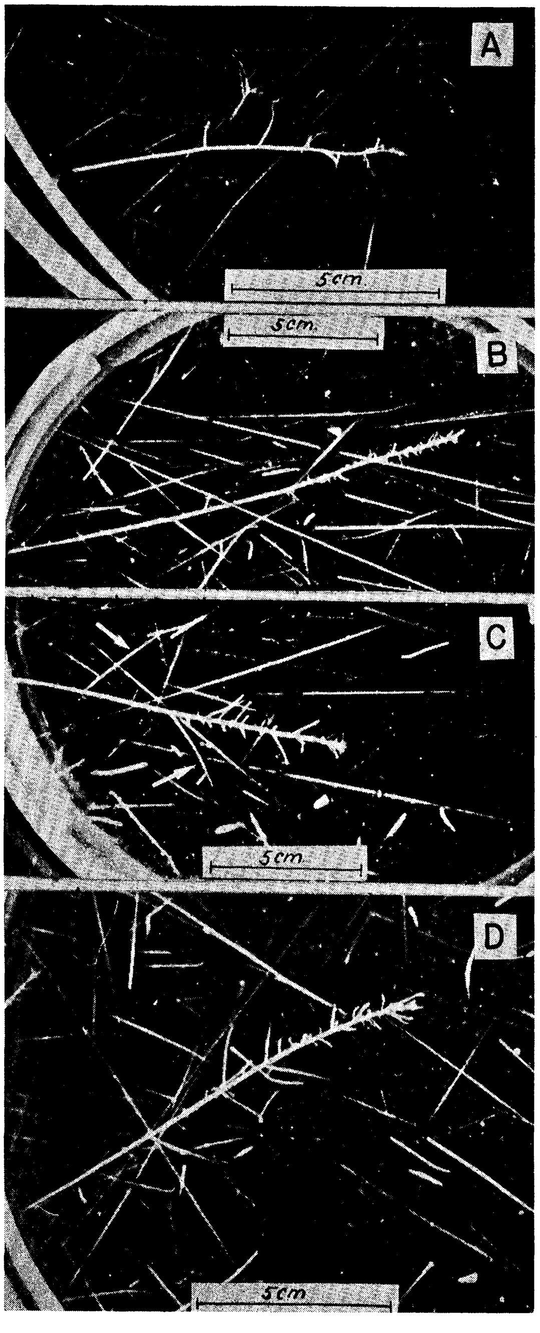

FIG. 1. A. Track in argon showing fortuitous bending and several branches all more intense than the protons and α-ray tracks appearing as background. Fine parallel lines are wires fastened to the underside of the glass cover to provide conducting surface for sweep field. ($A+H_2O+C_2H_6O$, total pressure 10 cm). B. Track in helium showing a close collision with a helium nucleus rather early in the range and numerous collisions on the last part. C. Track with several long helium branches suitable for velocity determination especially the two indicated by arrows. D. Track in helium with at least 30 collisions giving branches of more than 2-mm range. The forked track in the center of the picture is not a branch but a helium recoil nucleus produced by neutron impact and colliding after a path of few mm in the chamber with another helium nucleus. (B—D : $He+H_2O$, total pressure 34 cm.)

involved in the collision and of the knowledge of the range-velocity relation for these particles. The branch statistics gives information about the range-velocity relation by simply counting in various sections of the range the number of branches with lengths within given limits. This number is, in fact, inversely proportional to the square of the average velocity of the fragment in the respective range section. This method has the advantage that it is independent of other information, but the velocity determinations are only relative.

In the investigation of the range-velocity relation in argon the statistical method was mainly used, since the mean error of the direct velocity determination even under the most favorable conditions was about 20–30 percent. In helium, however, the direct velocity determination is practicable with greater exactness due to the fact that the collisions with helium nuclei are rather easy to distinguish from collisions with heavier and lighter atoms present in the cloud chamber. In the present investigation, both methods of velocity determination could therefore be used and gave results supporting each other. The experimental arrangement was the same as that described in the previous papers with the only difference that the water-alcohol mixtures used at that time were now replaced by pure water in order to reduce the stopping power of the vapor in the cloud chamber. The uranium was placed as a "thick" layer on a copper strip near the wall of the chamber.

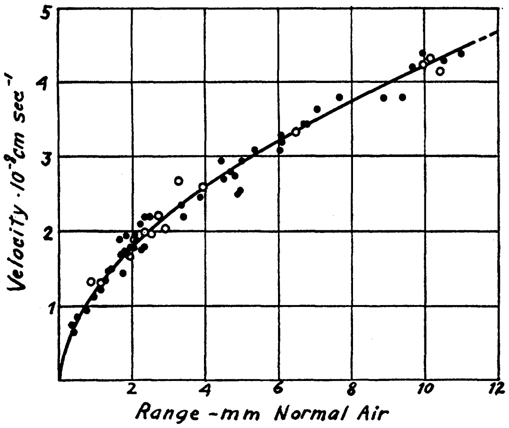

FIG. 2. Range-velocity curve in helium derived from individual close collisions with helium nuclei (full circles) and with heavier nuclei (open circles).

The determination of the velocity of the fragments 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 fission fragment, $u$ and $v$ are the velocities of these particles after the collision, and $\theta$ is the angle between the direction of the stem of the track before the collision and the direction of the branch. In collisions with helium nuclei the velocity $u$ was yielded by means of the energy-range relation for $\alpha$-particles,[4] the range of the helium branches being converted into normal air values by use of the stopping power coefficient of the gas. This stopping power was measured directly by means of a beam of $\alpha$-rays with a residual range of 12.5-mm normal air, admitted through a window in the side of the chamber. Since the stopping power of the gas turned out to be somewhat larger than it would corresponding to pure helium and water vapor, the helium gas was examined spectroscopically and was found to contain some nitrogen. Therefore, in the collisions with heavier nuclei, the mass was estimated to be 15, and the velocity $u$ was determined by a curve halfway between the range-velocity curves for oxygen and nitrogen of Blackett and Lees[5] with the values of the velocity increased by 5 percent.[6]

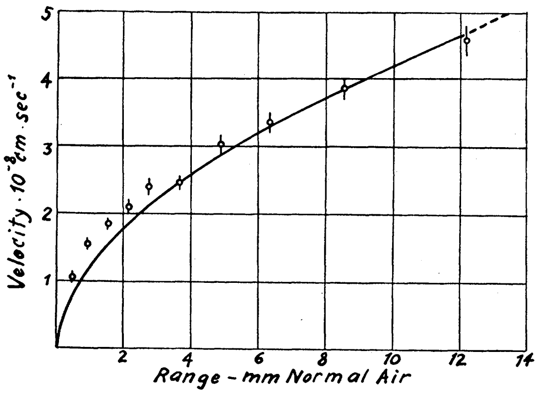

FIG. 3. Range-velocity relation in helium derived from statistic of branch distribution.

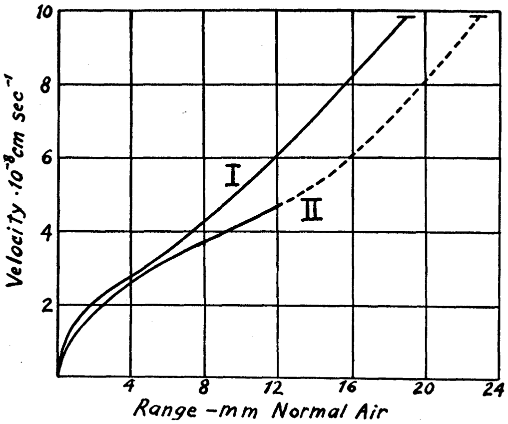

FIG. 4. Range-velocity relation in argon (curve I) and in helium (curve II).

The present investigation includes 34 fragment tracks at about 25-cm gas pressure and 83 fragment tracks at about 34-cm pressure. Among these, 49 collisions with helium nuclei and 15 with heavier nuclei are suitable for velocity determination; the results of these measurements are reproduced in Fig. 2, where the velocity is given in relation to the residual fragment range converted into normal air. The small full circles refer to the collisions with helium nuclei and the open circles refer to the collisions with heavier nuclei, and it will be seen that the two kinds of collisions within the experimental errors give consistent velocity determinations. The curve drawn on Fig. 2 to fit all the points as closely as possible must be taken as an average curve for the range-velocity relations for the lighter and heavier groups of fission fragments, and the relatively small spread of the points shows that the velocity curves of the two fragments differ only little within the last 10 mm of the range.

The experimental material was also subjected to a statistical examination on the basis of 83 tracks at 34-cm gas pressure, including in all about 1100 branches of length between 2.3 and 10 mm, i.e., 0.26–1.14 mm normal air. The relative velocities thus calculated are reproduced in Fig. 3 in such a scale that for the larger velocities agreement is obtained with the range-velocity curve derived from the direct velocity determinations which is here reproduced from Fig. 2. The circles with the vertical lines represent mean values and probable errors of the relative velocities. Although the points fall

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[4] Cornell University curves (1938).

[5] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. **A134**, 660 (1931).

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

rather close to the curve, the deviations for the smaller velocities are larger than the estimated experimental errors indicating some minor defects in the one or the other of the two methods of velocity determination. In the statistical method such a defect might perhaps be due to a failure to count all branches in the last, more branching part of the range; in the direct method a defect might be due to a possible inaccuracy in the assumed range-velocity relation of the $\alpha$-particles in helium for the smallest velocities.

A comparison of the range-velocity relation in argon and in helium is attempted in Fig. 4. Here, curve I is an average range-velocity curve for the two groups of fission fragments in argon obtained in the previous paper. In curve II, the full-drawn part corresponds to the information contained in Fig. 2, while the dotted part is drawn in a way that the total average range is 4-mm normal air greater than in argon, in accordance with the earlier measurements. Although the information on which the upper parts of curves I and II are based is rather scanty, it seems that there can be no doubt about the general run of the curves. In particular, the point where the rate of velocity loss is a minimum is obviously much farther removed from the end of the range in helium than in argon. The shape of the curves seems altogether to fit the theoretical expectations, and the curves can, at least within the experimental errors, be drawn in such a way that the rate of velocity loss is alike in the two gases in the first part of the range where the stopping is mainly due to electron encounters, whereas the end part of the range-velocity curve in helium is considerably longer than in argon, corresponding to the effect of the smaller energy loss by nuclear collisions in helium than in argon.

The author wishes to express his heartiest thanks to Professor Niels Bohr for his constant interest in this work and for many helpful discussions. I am also much obliged to Dr. E. Rasmussen for the spectroscopical analysis of the helium and to Mr. K. Lindberg-Nielsen and Mr. H. Arrøe whose assistance in the experiments has been of great value.

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# On the Pseudoscalar Mesotron Theory of β-Decay

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The calculations of Sakata which indicate that the pseudoscalar mesotron theory can successfully account for both mesotron decay and $\beta$-decay are shown to be in error. While the pseudoscalar mesotron theory gives the correct spin and parity selection rules for $\beta$-decay, it also gives $\beta$-decay lifetimes too long by a factor of $10^6$ and having an inverse seventh power dependence on the upper limit of the $\beta$-spectrum. As these same conclusions can be made when the mesotron field is strongly coupled to nuclear particles, it would seem that they are sufficient to show that pseudoscalar mesotrons are not responsible for $\beta$-decay.

YUKAWA'S[1] suggestion that $\beta$-decay is to be interpreted as the emission of a mesotron by a neutron (or proton) and its subsequent decay into an electron (or positron) and a neutrino has received support from the observed instability[2] and apparent $\beta$-radioactivity of cosmic-ray mesotrons. However, before it can be regarded as a correct description of nuclear $\beta$-processes, it must give rise to a theory of $\beta$-decay possessing the following features: (1) Fermi energy distribution[3] with its consequent inverse fifth power dependence of the lifetime on the upper limit of the spectrum,[4] (2) Gamow-Teller selection rules,[4, 5]

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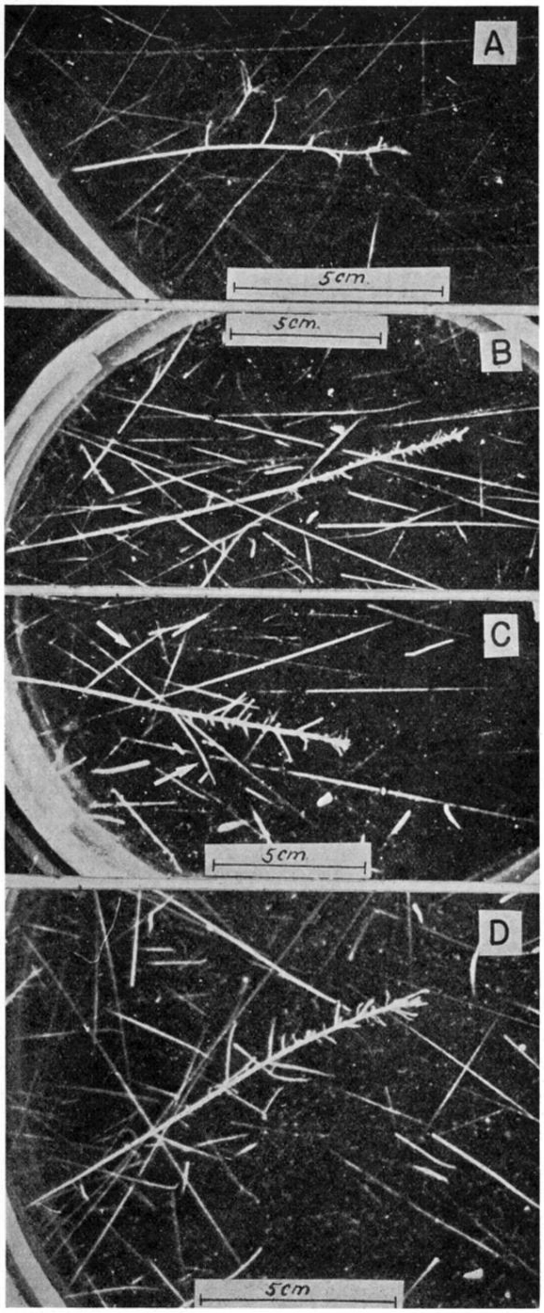
[1] H. Yukawa, Proc. Phys. Math. Soc. Japan **17**, 48 (1935).

[2] H. V. Neher and H. G. Stever, Phys. Rev. **58**, 766 (1940); B. Rossi and D. B. Hall, Phys. Rev. **59**, 223 (1941); W. M. Nielsen, C. M. Ryerson, L. W. Nordheim, and K. Z. Morgan, Phys. Rev. **59**, 547 (1941); F. Rasetti, Phys. Rev. **60**, 198 (1941); E. J. Williams and G. E. Robert, Nature **145**, 102 (1940).

[3] J. L. Lawson, Phys. Rev. **57**, 982 (1940).

[4] M. G. White, E. C. Creutz, L. A. Delsasso, and R. R. Wilson, Phys. Rev. **59**, 63 (1941).

[5] T. Bjerge and K. J. Brostrøm, Kgl. Danske Vid. Sels. Math.-fys. Medd. **16**, No. 8 (1938).



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