where $W(R)dR$ is the probability that the range has a value between R and $R+dR$; and R_0 is the mean value of the range, while ρ is a numerical constant approximately given by

$$\rho^2 = 3M_1M_2/4(M_1+M_2)^2. \quad (11)$$

For helium and argon (11) gives values of ρ equal to 0.16 and 0.37, respectively. Although the relative straggling is thus more than twice as large in argon as in helium, the absolute straggling of the range should be nearly the same, since the value for R_0 for the sensitive end part of the range should be about three times as large in helium as in argon. According to the above estimate of the fraction of the range where nuclear collisions constitute the preponderant stopping effect, we should expect $R_0\rho$ for both gases to be about 5 percent of the total range, in good agreement with the experiments which give for argon, as well as for helium, a straggling of this order of magnitude.[8, 10]

The various considerations here indicated are treated in greater detail in a paper shortly to appear in the Communications of the Copenhagen Academy of Science.[11] Especially is a closer discussion given there of the applicability of simple mechanical arguments for the treatment of the stopping and scattering of heavy highly charged atomic particles as well as of the ionization and electron capture by such particles.

Note added in proof.—After the present paper was sent from Copenhagen, we received here the issue of *The Physical Review* of October 15, 1940, which contains an article by W. E. Lamb on the passage of uranium fission fragments through matter. In main features the considerations of this article correspond to the arguments developed here and similar results are obtained. The treatment differs, however, at various points which will be commented upon in the fuller paper referred to above[11] where, also, the results of various experimental investigations not known in Copenhagen when the recent publications from this Institute were completed will be discussed.

[11] N. Bohr, Kgl. Danske Vid. Sels. Math.-fys. Medd. (Math.-phys. Comm., Acad. Sci. Copenhagen), **18**, 8 (1940).

FEBRUARY 1, 1941 PHYSICAL REVIEW VOLUME 59

Range and Straggling of Fission Fragments

J. K. Bøggild, K. J. Brostrøm and T. Lauritsen
Institute of Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

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As reported in an earlier note to *The Physical Review*,[1] a study of the tracks of uranium fission fragments in a cloud chamber filled with argon gas has yielded evidence for two groups of tracks corresponding to the two types of fragments known from direct measurements of their kinetic energies and for chemical analysis of the radioactive products. Direct measurements of the ranges of fragments expelled in both directions simultaneously from thin uranium targets on thin foils in the cloud chamber gave some indication of two groups. Also, a statistical analysis of the number of side branches along the ranges of a large number of tracks from thick targets showed clearly the presence of two different kinds of tracks, of which the one had two to three times as many branches at the other over most of the range, while near the end, the numbers of branches were more nearly equal. On the basis of general considerations regarding the course of the range-velocity curves and the relative charges of the fragments, it was concluded that the heavier particle had the more branches and the shorter range, corresponding to its higher charge and lower initial velocity. Further experiments, both in argon gas[2] and in

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

[2] The work on argon is more fully reported in the Kgl. Danske Vid. Sels. Math.-fys. Medd. (Math.-phys. Comm., Acad. Sci. Copenhagen) **18**, 4 (1940).

helium, have yielded more information concerning the grouping, confirmed the assignment of the larger number of branches to the short track, and permitted a comparison of the stopping powers of argon and helium for fission fragments.

Thin evaporated layers (about 0.2 mg/cm^2) of uranium on mica foils mounted in the center of a 25-cm cloud chamber were bombarded with slow neutrons and the tracks of both fragments from a given fission process photographed stereoscopically. The stopping power of the gas was determined by measuring the ranges of polonium α-rays, admitted through a window in the side of the chamber. The results of range measurement on 8 pairs and 20 "half-pairs" (in which one member did not end in the illuminated region of the chamber) in argon and 10 pairs and 10 "half-pairs" in helium are given in the accompanying histograms (Fig. 1). The two groups with opposite cross-hatching represent simply the shorter and longer member of each pair while the double cross-hatched groups on the right represent the sums of the ranges of the pairs. While the histograms for the individual members show only little separation into two groups, the grouping is clear from the relatively small spread of the sums. The breadth of this spread is, in fact, a measure of the straggling which is practically independent of the possible variations in grouping as regards the masses and initial velocities of the fragments. Thus, if the fragments from a given fission process had the same average range, the straggling of the individual members should be roughly $\sqrt{\frac{1}{2}}$ of the spread in the sum, while the actual variation of the measured values is nearly three times this amount. On the other hand, the data are quite well fitted by the assumption of two groups, each with a straggling of about $\sqrt{\frac{1}{2}}$ that of the

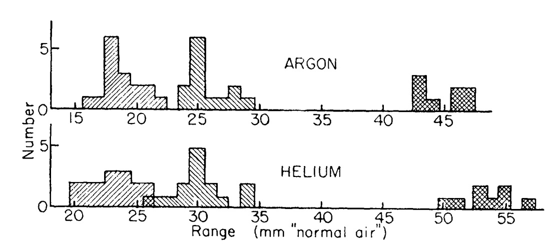

FIG. 1. Ranges and sums of ranges of paired fragment tracks, relative to ranges of α-rays of similar velocities.

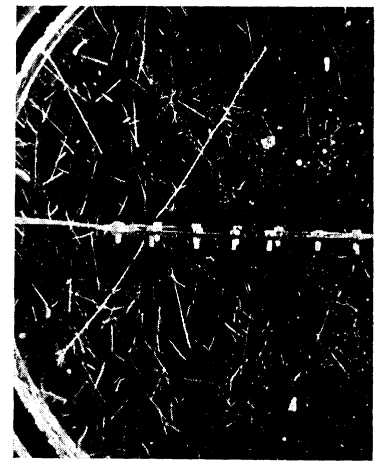

FIG. 2. Typical pair of fragment tracks in helium at 1.3 atmos. pressure. Tracks originate in upper side of 1.2 mg/cm^2 mica foil. Total length about 13 cm.

sum group. There is, in fact, no indication that the spread of the groups is essentially larger than this value, in conformity with other evidence which shows that the excited uranium nucleus always divides in approximately the same way. It is interesting to note that the straggling is approximately the same in helium and in argon, estimated as well from the range-sums as from the ranges of individual groups of fragments. The straggling in the latter groups is perhaps a little greater than corresponds to that of the range sums, because of the finite thickness of the uranium layer which, of course, has no influence on the range sums.

In argon, the mean ranges of the two groups, referred to normal air as defined by the stopping of α-particles, are 19 and 25 mm,[3] while the corresponding values in helium are 23 and 30 mm. The difference of about 20 percent between the values for argon and helium is an indication that the stopping power of helium relative to argon is lower for fission particles than for α-particles, presumably because of a smaller rate of velocity loss towards the end of the range, where the stopping is determined by nuclear collisions. As explained in the preceding article by Professor N. Bohr,[4] the stopping power for

[3] The values reported in the previous note have been reduced by corrections to the stopping power of the gas in the cloud chamber.

[4] N. Bohr, Phys. Rev. **59**, 270 (1941) (preceding paper).

fission fragments relative to that for α-rays should, in fact, be nearly the same over the whole part of the range where the stopping is mainly caused by electronic encounters. There it is also pointed out that the straggling must be ascribed practically entirely to the end part of the range, where the effect of nuclear collisions is predominant. It is just because of the relatively greater length of this part of the range in light gases that the resultant straggling in the total range is approximately the same in helium and argon.

Corresponding to the statistical analysis of the branch distribution on the argon tracks, an examination of the branch distribution was also made in helium. We have here not much material from cloud-chamber pictures at low pressure but, fortunately, since in helium the branches are relatively longer in comparison with the length of the whole track, it was possible to perform the analysis at the relatively high pressures used in the range determination of the tracks from thin uranium targets. This circumstance gives the advantage that the separation into groups need not be made by indirect statistical methods but can be based directly on the difference in range. The photograph (Fig. 2) shows a typical example of the paired fragment tracks in helium, with several branches on each member.

The results of the counts indicated a preponderance in branches of the shorter track, with a factor of about 1.5 near the end of the range, and about 1.8 over the remainder of the range. While the number of branches—about 120 in all—is too small to justify definite conclusions, the agreement with the previously estimated values is satisfactory and may be considered to support the general character of the range-velocity curves of the two groups of fragments. A comparison of the absolute numbers of branches within definite energy limits near the end of the range in argon and in helium also gave good agreement with the theoretical expectations.

The authors' sincerest thanks are due Professor Niels Bohr, under whose direction this work has been carried out and whose constant encouragement and active help has made it possible.

FEBRUARY 1, 1941 PHYSICAL REVIEW VOLUME 59

Protons from the Deuteron Bombardment of the Separated Isotopes of Chlorine

E. F. SHRADER* AND ERNEST POLLARD
Sloane Physics Laboratory, Yale University, New Haven, Connecticut

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The bombardment of chlorine by 3.2-Mev deuterons is found to give rise to several groups of protons and possibly to one group of alpha-particles. By bombarding targets in which the proportion of heavy chlorine was more than doubled an assignment of some of the groups has been possible. The assignment of Q values is as follows. $Cl^{35}(dp)Cl^{36}$: 6.31; 5.35; and 1.50 Mev. $Cl^{37}(dp)Cl^{38}$: 4.02; 3.02; 2.10. These figures lead to masses of 35.9808 and 37.9806 for the isotopic masses of Cl^{36} and Cl^{38}, respectively. A group which appears at 12 cm range we assign to the light isotope according to the reaction $Cl^{35}(d\alpha)S^{33}$. The Q value is 9.1 Mev which gives a mass of 32.9828 for S^{33} in reasonable agreement with the mass derived from the $S^{32}(dp)S^{33}$ reaction.

INTRODUCTION

THE fact that the bombardment of chlorine by deuterons would give rise to protons has been known, since both the isotopes Cl^{36} and Cl^{38} have been prepared by this reaction.[1] The direct detection of the protons and the measurement of the ranges of the resulting groups is of interest since it permits information

* Now at the Case School of Applied Science, Cleveland, Ohio.

[1] D. C. Grahame and H. J. Walke, see Livingood and Seaborg, Rev. Mod. Phys. **12**, 35 (1940); F. N. D. Kurie, J. R. Richardson and H. C. Paxton, Phys. Rev. **49**, 368 (1936).

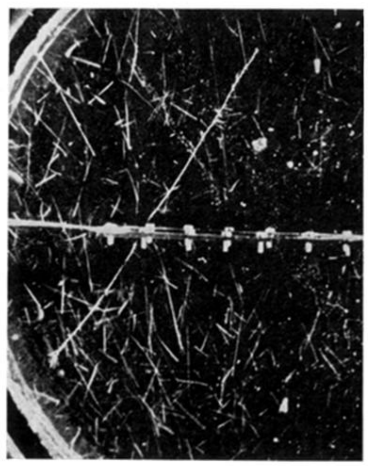

FIG. 2. Typical pair of fragment tracks in helium at 1.3 atmos. pressure. Tracks originate in upper side of 1.2 mg/cm^2 mica foil. Total length about 13 cm.