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DEDICATED TO PROFESSOR NIELS BOHR ON THE OCCASION OF HIS 60TH BIRTHDAY

ON THE EFFECTIVE CHARGE OF FISSION FRAGMENTS

BY

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(1) Introduction.

Since the discovery of the fission phenomenon by HAHN and STRASSMANN[1] in 1938 the properties of the fission fragments have been investigated in many ways. At an early stage it was suggested that the fission particles are thrown apart with very high kinetic energies, and this was experimentally established by FRISCH[2] and many others. Later on, the masses, energies, and ranges of the fission particles have been more closely studied by means of ionization chambers. The atomic numbers of several fission products have been determined by chemical means and in this way information about the charges of the fission nuclei has been obtained.

The charge of the fission nucleus is not the same as the effective charge of the fission fragment, because the fission nucleus does not travel alone but is accompanied by a number of the electrons from the original atom. As a result of the large energy and rather short range the specific ionization of the fragments is very great as compared with that of α-particles, which also was found by investigators using a cloud chamber, for instance BØGGILD, BROSTRØM, and LAURITZEN;[3] therefore the particles may be supposed to have a rather high charge, i. e. only a fraction of the electrons from the original atom accompany the nucleus. The magnitude of the effective charge was early assumed to be about 15—20 ε, where ε is the electronic charge, this being the result obtained by using Bethe's relation for energy loss per cm. range of heavy particles,[4] although, as we have not to do with a single heavy particle, but with a nucleus and a cluster of electrons, the use of this relation may be somewhat problematic; the rate of energy loss along range indicates that the effective charge in the beginning decreases rapidly because of capture of electrons.[3 and 5]

Unpublished calculations by Prof. Bohr based upon the assumption that those electrons in the uranium atom which have velocities smaller than the initial velocities of the fission fragments are left back while the others follow the fragments show that the initial effective charge of the particles has a value of about 20 ε; further calculations indicate that the charge decreases rapidly along the first part of the path and then is rather low, about unity along the rest of the path.[5]

The experiments to be described in the present paper give some information about the initial effective charge. Fission fragments from a thin layer of uranium were deflected in a magnetic field and the values of $H\varrho$ were determined. An experimental determination of the initial effective charge of the fission particles has previously been made by Perfilov,[6] who also measured the deflection of the fragments in a magnetic field and in close agreement with the above mentioned estimates found a value of 20 ε. However, as the result was rather uncertain, the estimated error being 20 per cent. and the paths of only 7 particles being determined, it was found desirable to repeat the experiments.

(2) Experimental Arrangement.

The target of uranium was placed in the cyclotron about 6 mm. behind a target of beryllium, which was bombarded with 6 *MeV* deuterons, thus being a strong source of neutrons. The magnetic field of the cyclo ron was used to deflect the fission particles and the paths of these were determined by means of the arrangement shown in fig. 1. In this is seen the brass ring (1) of the cyclotron chamber; (2) is a stud on this consisting of a 3-inch copper tube and a flange, (3) is a cylindrical chamber made of a piece of a 5-inch copper tube and a brass flange, which fits to the stud; the chamber is closed by the brass disk (4), in which is cut a slit. Inside the chamber there is the same pressure as in the cyclotron, the slit being covered with a window of mica and the connections (5) being made tight by means of rubber rings and glyptal. (6) is a second chamber, a $4\frac{1}{2}$ inch brass tube with a bottom and a flange; the space inside this chamber is filled with nitrogen taken from a steel tank with commercial nitrogen carefully cleared of oxygen by means of red-hot copper

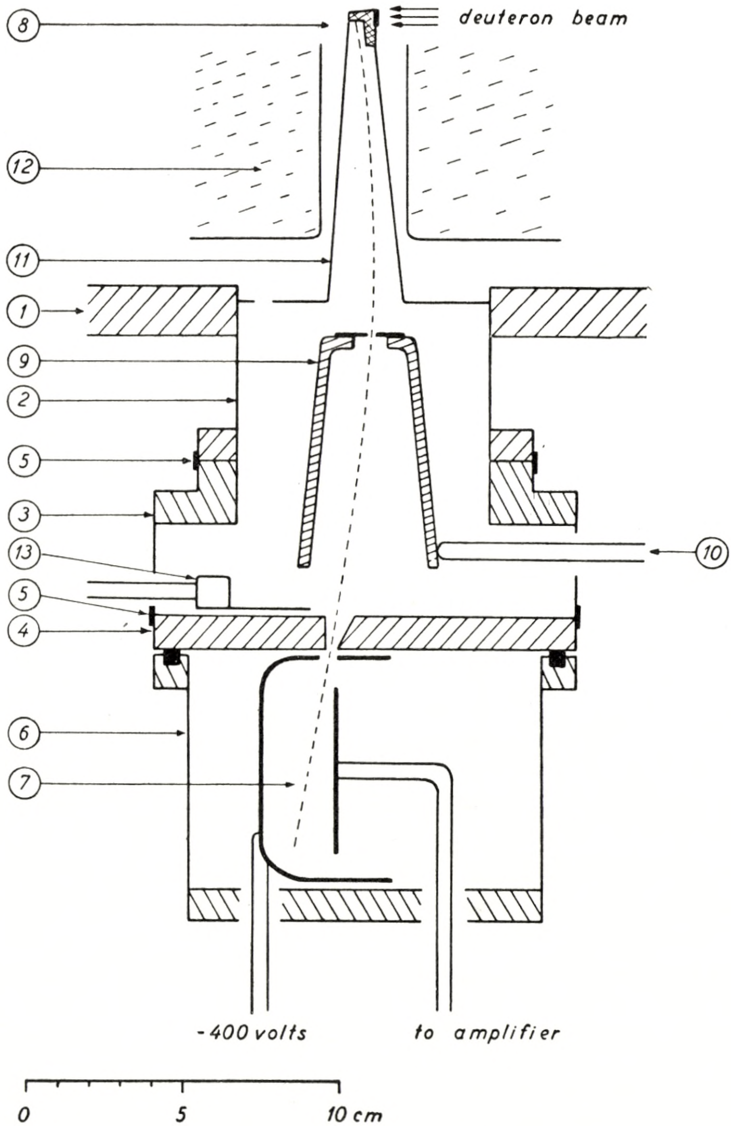

Fig. 1. Experimental arrangement. Horizontal section.

and of water by means of sulphuric acid. A slow stream of nitrogen through the chamber was maintained during the experiments. (7) is the ionization chamber. The beryllium and uranium targets are placed on a water-cooled copper block (8). Before entering the ionization chamber the fission particles must pass through the mica window and through a second slit—which in what follows is referred to as the slit—made from two knives supported by the brass plate (9), which is fastened on a movable slide (not shown in the figure) and can be operated from outside by means of the brass rod (10), against which it is pressed by a spring. The position of the brass rod and therefore of the slit can be read on a scale with an accuracy of 0.1 mm. (11) is a shield, which prevents scattered deuterons from entering the ionization chamber, (12) denotes the dees of the cyclotron and (13) is a combined diaphragm and holder, which can be operated from outside and put in five positions with the following consequences: In the first position the window is entirely free, in the second the free length of the window is reduced to one half, the other half being covered by the diaphragm, and in the third position the window is entirely closed; in the fourth position a rather large target of uranium is placed just outside the window, and finally in the fifth position this target is replaced by an α-gun to be described later.

The beryllium target was prepared from metallic beryllium, which was available as a crystalline powder. The powder was placed in a cylinder of iron closed with a piston and in an atmosphere of hydrogen heated to a temperature of about 800° C. and then forged to a pill, which was ground off and soldered to the copper block, ammonium chloride being used as a flux.[7] Several other methods of preparing the target was tried, but with no success, and though this procedure is rather tricky, it was found possible to get good targets in this way. The target must be rather thin, about 0.5 mm., so that the heat may be easily transmitted; it is very difficult to melt the beryllium outside the cyclotron, but very easy to do so inside it. For the same reason the copper block must be very effectively cooled; in the arrangement used this requirement was not perhaps entirely fulfilled, as it was supposed to be of more importance that the distance between the beryllium target and the uranium one was kept short and that the direction between the two targets did not diverge too much from the direction of the deuterons; as a consequence it was necessary to keep the energy input of the cyclotron oscillator rather low in order to avoid destroying the beryllium target by melting or evaporation.

The uranium target was made by evaporation *in vacuo* of uranium powder, which was placed on a tungsten band with a width of 5 mm. and the temperature of which was slowly raised to incandescence; the target plate was held at a distance of 5 cm. and in the beginning protected by a screen, which was removed by means of a magnet when the temperature had reached its final value; in this way most of the impurities of the uranium powder—12 per cent.—were prevented from reaching the target. Two targets were used, target I on a support of copper sheet, target II on a support of mica sheet. The dimensions were for I 20 × 1.3 mm.^{2} and for II 20 × 0.7 mm.^{2}; the thicknesses of the two layers were nearly the same, about 0.35 mg. per cm.^{2}, as determined by a counting of the α-particles.

The width of the slit, which can be varied from 0 to 8 mm., will be mentioned in each case.

Two brass disks (4) were made. In one of them (I) the window had a width of 4.0 mm. and a length of 66 mm. with three 2 mm. cross bars, the effective opening thus being 4.0 by 60 mm.^{2}. In the second (II), the window had a width af 2.0 mm. and an effective length of 56 mm. The mica was placed between the brass disk, which was carefully polished, and a frame of 0,5 mm. copper, piceïn being used for fastening and tightening. Several windows were used, in the beginning with thicknesses of about 1.5 mg. per cm.^{2}; although the splitting of this rather large mica sheet is a tedious process, it was soon found desirable to use thinner windows. Precautions then had to be taken to keep the difference of pressure on the two sides of the window below some 20 cm. of *Hg* during the evacuation of the cyclotron after the apparatus had been put in place; except when used the windows were submitted to a pressure difference of about one cm. of mercury, of course always in the same direction. The results mentioned in what follows were obtained with a window of type I with a thickness of 0.93 mg. per cm.^{2} and a window of type II with a thickness of 0.73 mg. per cm.^{2}

The amplifier contained three stages, the two last of which for convenience were placed at some distance from the cyclotron, the first being placed in a tube stiffly connected with the ionization chamber. As in the actual ionization chamber nothing could be changed without filling the whole cyclotron with air, a second chamber was used for testing, while the amplifier was built, and for some measurements, e. g. the determination of the thicknesses of uranium targets. The amplifier could be connected with a thyratron and a mechanical counter; however, in the experiments to be mentioned it was connected with a cathode ray oscillograph through an extra auxiliary amplifier; by varying the amplification of this extra amplifier it was possible to record both α-particles and fission particles without touching the actual amplifier. Some trouble was caused by electrical disturbances, the amplifier being placed in the same room as the 50 kW short wave oscillator of the cyclotron. Finally, all voltages were taken from batteries and the heating current from an accumulator, all shielded in metal boxes. The pulses on the oscillograph were recorded by a camera with a moving film. The developed films were put into a small diascope and the measuring carried out on the picture, this being in a standard position.

(3). Adjustment of the Amplifier.

The first thing to be done was to test the linearity of the amplifier and to adjust the arrangement. This was done by means of artificial pulses taken from a small machine, the diagram of which is given in fig. 2; C_2 is continuously charged

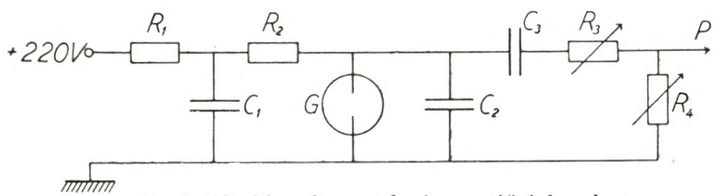

Fig. 2. Machine for producing artificial pulses.

R_1: $10^6\,\Omega$ R_2: $10^7\,\Omega$ R_3: $10^6 - 10^7\,\Omega$ R_4: 10^3—$10^5\,\Omega$
C_1: $4\,\mu F$ C_2: $0.25\,\mu F$ C_3: $50\,pF$ G a glim lamp.

through R_2, but when the potential reaches the critical value of the glim lamp G, it suddenly drops down again; part of the pulse is carried from the point P to a little condenser, which is in stiff connection with the grid of the first valve of the amplifier; the size of the transmitted pulse can be varied in steps from 1 to 100 in arbitrary units by varying R_4; the size of the units can be varied by means of R_3.

The adjustment was now carried out in the following way: An α-gun was made; the source of α-particles was *RaD* on a small piece of a mica window from an old radon source. By a diaphragm a narrow beam of α-particles was selected, which was allowed to enter the ionization chamber through the window in such a direction that none of the α-particles would hit the walls of the chamber; the range of the particles was reduced by means of an absorber of mica placed on the diaphragm of the gun.

In the case of window I the following data were obtained: Thickness of absorber and window $2.6 + 0.9 = 3.5$ mg. per cm.^{2} equal to $3.5/1.45 = 2.4$ cm. of air; the figure 1.45 as well as many other figures in what follows is found in a paper by LIVINGSTON and BETHE[8]. The range of the α-particle in the ionization chamber is found to be $3.8 - 2.4 = 1.4$ cm. of air, which is to be corrected to 1.35 cm., because the particles travel 0.2 cm. behind the window before entering the actual chamber, the pressure of which being 19 cm. Hg. Thus each of the particles delivers an energy of 2.5 *MeV* within the chamber, and this is found to correspond to pulses of 21.5 mm. as measured in the standard way previously described. The arbitrary unit of artificial pulses used being denoted with k, the following figures were found: 7, 14.4, 21.7, 27.6, and 34.6 mm. corresponding to $1k$, $2k$, $3k$, $4k$, and $5k$, respectively. The spreading about these values according to the background noise of the amplifier was the same, about ± 2 mm., whether the pulses were due to α-particles or were artificial. As a result of the adjustment we thus find that $1k$ corresponds to 0.84 ± 0.05 *MeV*, which of course is independent of the amplification. For larger values of the artificial pulses we get a little correction because in the machine R_3 is not infinitely large as compared with R_4.

This result could be reproduced, while it was found that the amplification was not entirely constant and the amplifier therefore had to be adjusted by artificial pulses rather often.

(4). Experiments with Geometry I.

The width of target and window are 1.3 and 4.0 mm., respectively. When the width of the slit is 1.3 mm., it is seen that a beam of particles travelling in straight lines and defined by the target and the slit will just fill the window; as the fission particles travel in lines with rather small curvatures nearly the same will apply to particles with the same $H\varrho$. In the experiments for determination of $H\varrho$ the slit therefore was 1.3 mm., and its position was changed in steps of 1.3 mm., ranging between -10.4 and $+22.1$, where 0 denotes the position in which the middle lines of target, slit, and window are in the same plane and the sign is chosen in such a way that positive particles are deflected against positive figures.

It was then found that for all positions of the slit the oscillograph showed a large number of pulses corresponding to energies up to about 10 *MeV*; these are ascribed to nitrogen atoms in the ionization chamber recoiling after collision with fast neutrons, or, more strictly speaking, to coincidences between several such recoil atoms. Only for a few positions of the slit essentially larger pulses were obtained, in magnitudes up to about 50 *MeV*, and these must be ascribed to fission particles from the uranium target entering the ionization chamber along the paths indicated in fig. 1, as was asserted in the following way:

(1) By means of the diaphragm (13) (fig. 1) it was immediately established that the pulses are due to particles entering through the window.
(2) Next, it was shown, by means of an arrangement (not shown in the figure) which permitted closing of the slit by turning the rod (10), that the particles pass through the slit.
(3) A test run without uranium target showed no such pulses, although the recording system surely was in proper order, as fission particles from the control uranium target on (13) could be recorded. Consequently the particles are coming from the uranium target.
(4) The pulses cannot be due to coincidences between α-particles as the number of those amonts to 0.05 per min. only, while the number of the large pulses are about 10 per min. Further the pulses are only observed when the cyclotron is running.

Thus the pulses corresponding to energies essentially higher than 10 *MeV* are undoubtedly due to fission fragments; however, as will be seen below, the lower energy limit of the fission pulses is probably smaller than the upper energy limit of the recoil pulses, and hence it is impossible to distinguish between the two sorts of pulses in the region from about 10 *MeV* and downwards.

Fig. 3 shows a copy of one of the recording films; several fission pulses are seen, both the actual primary pulses (upwards) and the secondary pulses after the return of the amplifier. When viewed visually on the oscillograph, the recoiling atoms are

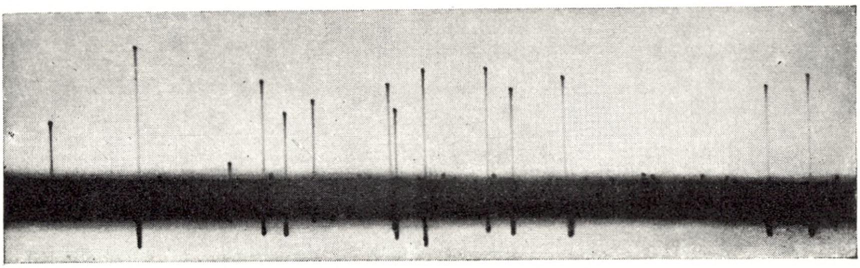

Fig. 3. A piece of a recording film.
The largest fission pulses correspond to about 50 *MeV*. The horizontal line is due to recoil atoms; its width corresponds to about 10 *MeV*, which does not determine the uncertainty of energy measurements (see text).

seen as a lot of pulses, but they appear in so large a number, that on the rather slowly moving film they cannot be separated, but produce the broad horizontal line, which, of course, does not determine the uncertainty of the energy measurements.

In fig. 4 are plotted the number of pulses larger than 12 *MeV* against the displacement of the slit, the number of course being referred to the same dose of neutrons; as regards the scale of $H\varrho$, see below. The neutron dose was measured by an instrument also used for managing the cyclotron; it consisted of an ionization chamber with boron layers on the plates, which was surrounded by paraffine and was connected with a galvanometer and with a recorder registering the electrical charge passing through the boron chamber, thus giving a measure of the number of neutrons in relative units (denoted in what follows as n. u.).

Fig. 5 shows the energy distribution obtained for the five positions of the slit giving reasonable yields, the numbers being referred to the same neutron dose of 1,000 n. u., which was about the dose used. The hatching to the left of the 12 *MeV* line indicates the pulses due to recoil atoms; as in the abscence of fission particles very few pulses a little larger than 10 *MeV* were recorded, most of the pulses in the region 12—16 *MeV* and all larger pulses are due to fission fragments. On the other hand some of the fission particles may have energies less than 12 *MeV*; nevertheless, as indicated by fig. 5, it seems permis-

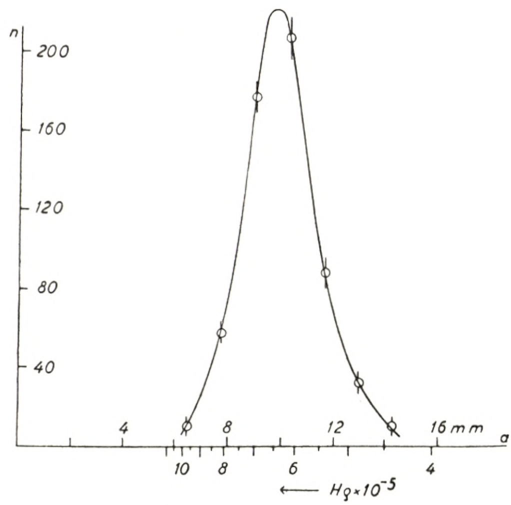

Fig. 4. Deflection curve for fission fragments obtained with geometry I.
Abscissa a: displacement of slit.
Ordinate n: number of fragments per 1,000 n. u.
Scale of $H\varrho$ in units of 10^5 oersted × cm.

sible to assume that this is only a small part of the total number, so that the correction which ought to be added to the numbers in fig. 4 may be omitted.

As is known from many previous investigations, two groups of fission particles exist, with different masses, energies, and ranges. Now, in fig. 4 only one peak is found, and therefore it might be suspected that only one of the two groups has been found and that a second group was lying outside the region which could be investigated by the apparatus, or that the second group had too little energy to be recorded after passing through the window. The former of these possibilities would involve an effective charge higher than 40 elementary units, which, from a theoretical point of view, would, indeed, be very surprising;

the latter would also be very astonishing, and in fact fig. 5 indicates that both groups of fission fragments are represented, the energy distribution curves clearly showing two peaks. The two groups have very nearly the same $H\varrho$ and therefore we get only one peak in fig. 4; still, it will be noticed that the

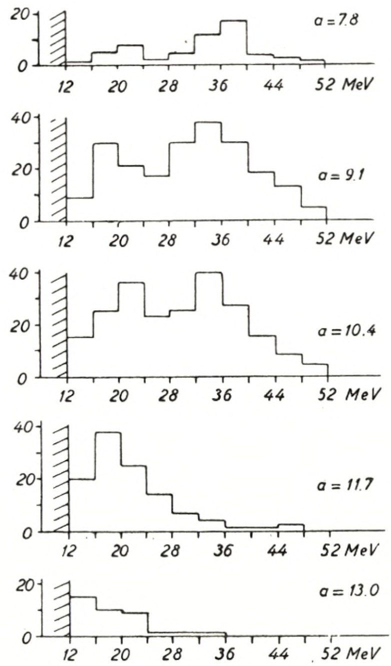

Fig. 5. Energy distribution of fission fragments for various positions of the slit (geometry I).

Ordinate: number of fragments per 1,000 n. u.
a: displacement of the slit in mm.

relative abundance of the two groups is not the same for the different positions of the slit, but that the most energetic is found to be predominant for the largest values of $H\varrho$. Since in the two groups corresponding particles have the same momentum, this means that in general the particles with the smallest masses have also the smallest effective charges; from an experimental point of view it may, of course, be an open question, whether this rule holds for each single fission process or not, but it certainly does so for some fissions, as the particles for $a = 11.7$ and 13.0 belong almost entirely to the heavy group, and they must have corresponding particles in the light group with the same mv and smaller values of a, i. e. smaller values of e. This seems to be in contradiction to the theory outlined by Prof. BOHR in the above-mentioned paper,[5] in which the formula for the effective charge is given as

$$Z^{\text{eff}} = Z^{\frac{1}{3}} \cdot \frac{V}{V_0},$$

Z and V being the nuclear charge and the velocity of the fragment, $V_0 = 2.2 \times 10^8$ cm. per sec. The light and the heavy fragment being denoted with indices 1 and 2, we get

$$\frac{Z_1^{\text{eff}}}{Z_2^{\text{eff}}} = \left(\frac{Z_1}{Z_2}\right)^{\frac{1}{3}} \cdot \frac{V_1}{V_2} \sim \left(\frac{m_1}{m_2}\right)^{\frac{1}{3}} \cdot \frac{V_1}{V_2}$$

and since $m_1 V_1 = m_2 V_2$

$$\frac{Z_1^{\text{eff}}}{Z_2^{\text{eff}}} \sim \left(\frac{m_2}{m_1}\right)^{\frac{2}{3}}.$$

Thus, a consequence of the theory is that the light particle has the higher effective charge; as now the theory was in good agreement with the experiments of BØGGILD, RROSTRØM and LAURITZEN, the present results at a first sight seem to be disagreeing not only with the theory, but also with the experiments mentioned. However, as already pointed out by Prof. BOHR in the paper, Z^{eff}, the charge effective in electronic interactions, may be different from the total charge of the fragment, e. In the deflection experiments we have to do with the total charge e, while the theory deals with the quantity Z^{eff}; therefore, strictly speaking we have no discrepancy, but we find that the two quantities behave inversely, as we have $e_1 < e_2$ and $Z_1^{\text{eff}} > Z_2^{\text{eff}}$.

The energy distribution for the total number of fission fragments of all $H\varrho$-values might be obtained by adding up the five curves of fig. 5; however, it was obtained in a more direct way by changing the width of the slit from 1.3 to 6.5 mm. and placing it in such a position that it covered the whole region through which the fission particles were passing. This arrangement was also used for some test experiments:

Firstly, the voltage of the ionization chamber was varied and energy distribution curves were determined for values of 200, 300, and 400 volts; the three curves were identical within the limits of statistical errors, this indicating that a voltage of 400 is enough to ensure saturation and a sufficiently short time of

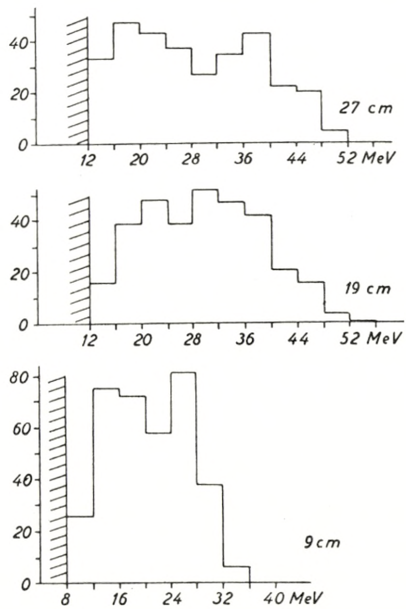

Fig. 6. Energy distribution obtained with various pressures in the ionization chamber.

collecting the ions as compared with the resolving time of the amplifier, which had to be rather small (10^{-4} sec.) in order to diminish the pulses due to coincidences between recoil atoms.

Secondly, the pressure in the ionization chamber was varied; the pressure generally used was 19 cm. *Hg*, but now energy distribution curves were determined for pressures of resp. 27, 19, and 9 cm. *Hg*. The result is shown in fig. 6; while the first two curves are almost identical, the last one deviates considerably, the maximum energy being decreased from 52 *MeV* to 36 *MeV*; this is in agreement with the expected residual range of about 1.5 cm. of normal air.

Fig. 7 gives the sum of all measurements of the energy distribution curve carried out with nitrogen pressure 19 cm. *Hg* and the one carried out with 27 cm. *Hg*. The two groups are clearly seen, although the valley between the two peaks is rather small as compared with the distribution obtained when the total energy of the fission particles is measured (see e. g. fig. 11 in the paper by FLAMMERSFELD, JENSEN, and GENTNER[9]). Of course this is at least partly due to the way in which the histogram is drawn with the rather large energy intervals of

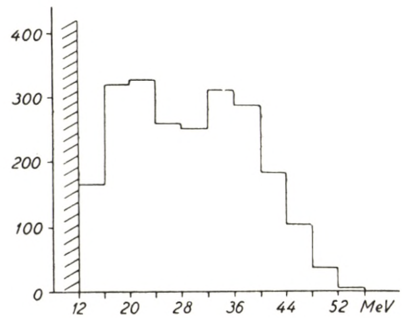

Fig. 7. Energy distribution of fission fragments having traversed 0.93 mg. per cm^2. of mica.

4 *MeV*; these were chosen because a test run with artificial pulses showed that the spreading of such pulses was less than ± 0.5 *MeV* with the cyclotron stopped, but increased to about ± 2 *MeV* with the cyclotron running. FLAMMERSFELD, JENSEN, and GENTNER find the maximum energy to be 106 *MeV*; now BÖGGILD, BROSTRØM, and LAURITZEN[3] give velocity-range curves for fission fragments, and a calculation on this base gives for the maximum energy of the particles having traversed 0.9 mg. per cm.^{2} of mica a value of about 55 *MeV* in good agreement with the value measured. The minimum energy cannot be calculated in the same way, as the result greatly depends upon the range, and this is not known with sufficient accuracy; however, the calculation gives a value between 10 and 20 *MeV* which is also in agreement with fig. 7 and which justifies the omission of the correction to the curve in fig. 4.

(5) Experiments with Geometry II.

Of course every geometrical arrangement with finite dimensions will tend to make the peak in fig. 4 broader and to conceal possible details. As the observed peak only extends over five positions of the slit, it was desirable to repeat the experiments with a geometry giving a higher resolution. This was performed with geometry II, in which each of the three significant dimensions, the widths of the uranium layer, the window, and the slit, determining respectively the amount of uranium, the solid angle, and the size of the $H\varrho$-intervals, was reduced to about half of the previous values, the yield of fission for each single position of the slit consequently being reduced to one eighth. The time and the costs are in this way increased by a factor of sixteen as the number of positions of the slit to be investigated is twice as large as before; therefore, it was not found possible to improve the geometry further.

The widths of the uranium layer and the slit were 0.7 mm. and the slit was moved in steps of 0.7 mm. The width of the window was intended to be 2.0 mm., this being the width of the slit cut in the brass disk (4) (fig. 1), but some of the piceïn used for fastening the mica foil happened to cover about 0.5—0.8 mm. along one of the edges, the actual width thus being about 1.4 mm.

It is important, when studying the initial effective charge, to get a thin target of uranium, but in order not to decrease the yield further, the new uranium layer was made of the same thickness as the first one, this being considered as a rather thin target. However, it was to be feared that, because of possible irregularities of the copper support, the effective stopping power of the layer might differ from the value determined from the amount of uranium; to avoid this the new target was made on a support of mica as already mentioned.

The result of the experiments is given in fig. 8 by the open circles and the curve. The region outside the peak on both sides was investigated with a slit of 6.5 mm.; nothing was found. The full circles in the figure are the circles from fig. 4 (geometry I), the ordinates having been reduced by a suitable factor, so that the total yield of fission particles of all values of $H\varrho$ is the same for each set of circles. The agreement between the two experiments is satisfactory. It is evident that when we use geometry I with the broad slit, etc., the curve must be broader, i. e. the full circles must lie outside the curve on both sides as is seen to be the case; hence it follows, from the way in which the ordinates of the full circles were reduced, that they must lie inside the curve for the middle a-values.

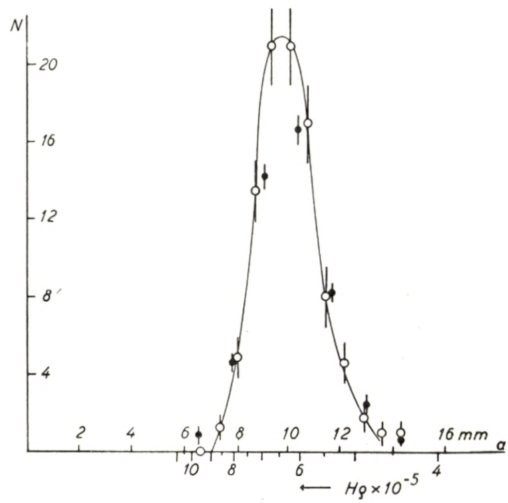

Fig. 8. Deflection curve for fission fragments obtained with geometry II (open circles).
Abscissa a: displacement of slit.
Ordinate: number of fragments per 1,000 n. u.
Scale of $H\varrho$ in units of 10^5 oersted × cm.
Full circles, see text.

By the determination of the curve on fig. 8 any uncertainty caused by an unknown correction was avoided as the pressure in the ionization chamber was kept at 9 cm. *Hg*, which reduced the background due to recoil atoms to 6—8 *MeV*, while, as the thickness of the window was now only 0.73 mg. per cm.^{2}, the smallest energies of the fission particles were about 10 *MeV*, a free space thus remaining between the two sorts of pulses.

The energy distribution curve in fig. 9 was determined in the same way as before, the pressure in the ionization chamber now being 23 cm. *Hg*. As before the two groups of fission fragments are clearly visible, and a comparison with fig. 7 shows that the energies are increased in accordance with the use of a thinner window.

As indicated by fig. 8, the two groups of fission fragments have so nearly equal $H\varrho$-values that they are not separated

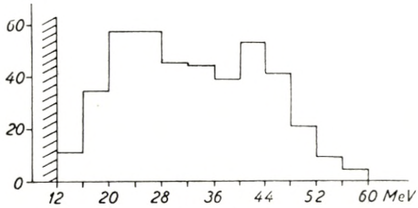

Fig. 9. Energy distribution of fission fragments having traversed 0.73 mg. per cm.^{2} of mica.

even with this better geometry. It was found desirable to investigate the energy distribution for the various positions of the slit corresponding to the experiments of fig. 5, but on account of the rather small yield this was only performed for two positions, which were chosen one on each side of the peak and so

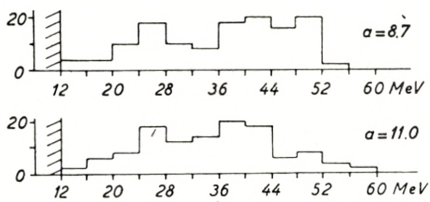

Fig. 10. Energy distribution of fission fragments for two positions of the slit (geometry II).

Ordinate: number of fragments per 6,000 n. u.
a: displacement of the slit in mm.

that the yield was about half the maximum yield. The distance a of the slit from zero position was resp. 8.4 and 10.7 mm., the width of the slit 0.7 mm. and the pressure in the ionization chamber 23 mm. *Hg*; the result is seen in fig. 10. The two curves are very nearly equal; still, if we divide the numbers into two portions with energies resp. lower and higher than 36 *MeV*, we find for the first curve ($a = 8.4$) resp. 27 and 38, and for the second curve ($a = 10.7$) resp. 30 and 29. Thus the difference between the two energy distributions, if any, is that in the first case, i. e. for the largest $H\varrho$, the most energetic group of fission fragments is more strongly represented than in the second case.

This is in agreement with the result found with geometry I; nevertheless, the difference between the two curves is scarcely greater than could be explained by statistical fluctuations, the material being much too small, and the only certain conclusion which can be drawn from fig. 10 is that both groups of fission particles are represented for both positions of the slit and in ratios not differing very much. This seems to indicate that we cannot expect to get a curve with two peaks even when the $H\varrho$-distribution curve was determined with a much better geometry.

(6) The Scale of $H\varrho$.

By the calculation of the scale of $H\varrho$ previous measurements of the magnetic field of the cyclotron magnet were used. At the starting-point of the fission fragments the field was very nearly the same as in the centre of the cyclotron, about 15,000 oersted, while at the end of the paths it had decreased to about 45 per cent of this value. Now the path of a particle with a fixed value of $H\varrho$ and starting along the radius of the cyclotron was calculated by means of analytical methods, the path being divided into a number of smaller portions with increasing values of ϱ corresponding to the decreasing H. The curve thus found was drawn to the scale of 3/1 on a piece of transparent paper, which was placed upon a drawing of the apparatus and rotated about the starting-point of the particles, until the curve passed through the central-point of the window; the intersection between the curve and the plane of the slit indicates the position of the latter corresponding to the value of $H\varrho$ concerned. This procedure was carried out for three values of ϱ and the result is shown in Table 1. The last column shows that the product $a \times H\varrho$ is a constant within the limits of error, as indeed was to be expected from simple geometrical considerations. As a mean value we get $a \times H\varrho = 63.0 \cdot 10^5$ and this is used to define the scale.

Table 1.

Initial ϱ	$H\varrho$	a	$a \times H\varrho$
50 cm	$7.40 \cdot 10^5$ oersted $\times$ cm.	8.4 mm.	62.2×10^5
35 -	5.18 -	12.1 -	62.7×10^5
25 -	3.70 -	17.3 -	64.0×10^5

In order to check the scale an experiment was made in which α-particles from ThC' were deflected in the apparatus. The uranium layer was replaced by a metal wire 0.7 mm. in diameter, which for some hours had been activated in an atmosphere of thoron, and measurements were performed in the usual way, the result being illustrated by the two curves in fig. 11. The α-particles from ThC' have an energy of 8.77 MeV; the relation $H\varrho = \frac{\sqrt{2\,mE}}{e}$ gives $H\varrho = 4.27 \cdot 10^5$ oersted cm. The displacement a as calculated by use of the scale is 14.8 mm., and the agreement between the scale and the experiment is seen to be rather good.

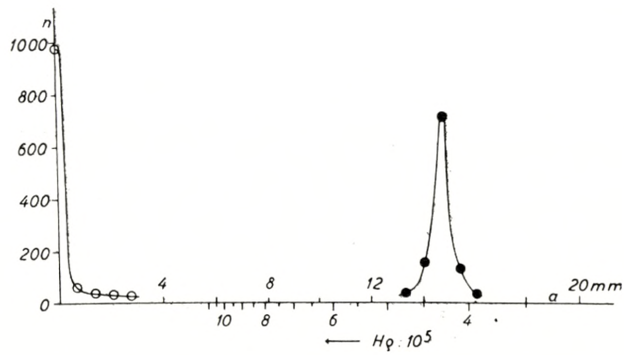

Fig. 11. Deflection of $Th\,C'\alpha$-particles measured by geometry II.
Abcissa a: displacement of slit.
Ordinate n: number of particles per min.
Open circles without magnetic field.
Full circles with magnetic field 14,800 oersted.

The areas beneath the two curves of fig. 11 of course are equal. In the case of the open circles we have to do with particles travelling in straight lines; the shape of this curve thus gives information about the resolving power of the geometry. The ordinate for $a = 0.7$ is about 7 per cent. of the peak value, which is exactly what can be calculated for geometry II, the width of the window being 1.4 mm.; for larger values of a we ought to get zero, while in the experiment a background was found of about 2 per cent. of the peak value. In the case of the full circles of fig. 11, the shape of the curve shows that the particles have not exactly the same $H\varrho$.

(7) The Value of the Initial Effective Charge *e*.

Fig. 12 gives the $H\varrho$-distribution curve as obtained by means of geometry II, considering the correction due to the fact that in the experiment da was constant, not $d(H\varrho)$. By using the relation $e = \frac{\sqrt{2\,mE}}{H\varrho}$ we could calculate e, if only we knew mE. This quantity may be calculated e. g. from the data of FLAMMERSFELD, GENTNER, and JENSEN; fig. 13 shows the curve thus found

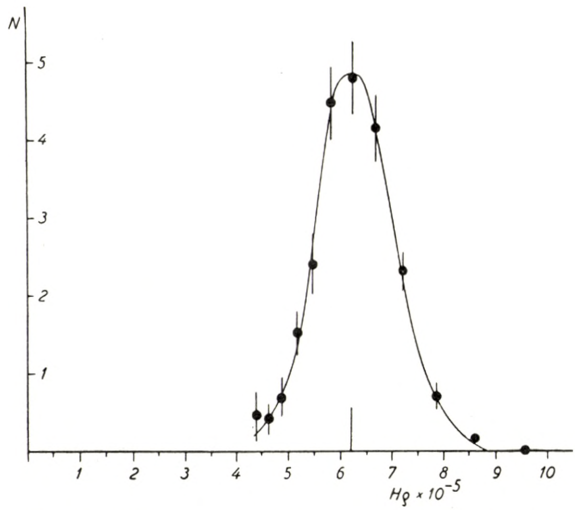

Fig. 12. Distribution of $H\varrho$ for fission fragments.

for the distribution of mE. Now we do not know exactly corresponding values of $H\varrho$ and mE; but combining the most frequent values $H\varrho = 6.2 \cdot 10^5$ oersted $\times$ cm. and $mE = 8.5 \cdot 10^3$ mass units $\times$ *MeV* we get $\underline{e = 21\,\varepsilon}$ and putting the limits of mE at 6.5 and 10.5×10^3 we find that the particles having $H\varrho = 6.2 \cdot 10^5$ have effective charges between 19 and 24 ε. Combining the limits of $H\varrho$, 4.5 and $8.5 \cdot 10^5$ with the limits of mE we find:

(1) e lies between 13 ε and 33 ε except for a very few particles, and
(2) There exist particles corresponding to every e-value, of course only full numbers, between 18 ε and 26 ε.

Roughly spoken fig. 8 may be said to give a picture of the distribution of e, as we may write $mE = 8.5 \cdot 10^3 \pm 25$ per cent., that is to say $e = \frac{\text{constant}}{H\varrho} \pm 13$ per cent, or $e' = 2.1 \cdot a \pm 13$ per cent.

Flammersfeld and co-workers used slow neutrons to produce fission, while in the present experiments the neutrons were rather fast, and therefore it is not, of course, quite permissible to combine the values of $H\varrho$ and mE in the way shown; nevertheless it is known[10] that the energy distribution of the fission particles does not vary much with the energy of

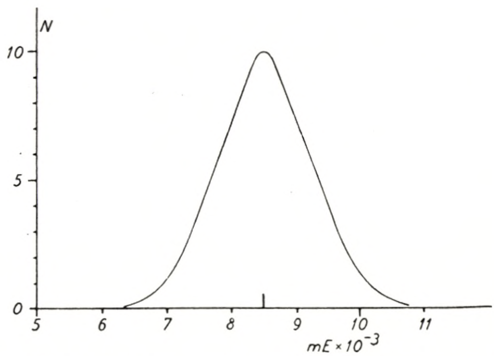

Fig. 13. Distribution of mE for fission fragments.

the neutrons, so that we may expect the calculated e-values to be rather good.

(8) **Summary.**

By means of the cyclotron magnet fission fragments from a thin layer of uranium were deflected; the deflection curve consisted of one single peak and energy distribution curves showed that both groups of fission particles were present, i. e. the two groups have nearly the same $H\varrho$. The experiments further showed that the two groups have not exactly the same $H\varrho$, the most energetic group being predominant for the highest $H\varrho$-values, i. e. the fragment with the smallest mass generally has also the smallest effective charge. By the aid of a better resolving geometry an attempt was made to separate the two groups, but in vain; the two experiments agreed well with each other. From the $H\varrho$-distribution thus determined and the distribution of mE as derived from the paper of Flammersfeld, Gentner, and Jensen, the value of the charge e was calculated.

The result of the experiments, an effective charge of about 21 ε, is in good agreement with the calculation by Prof. Bohr mentioned in the introduction. Still, the theory gives a higher effective charge for the lighter fragment than for the heavier, while the opposite was found in the experiments; nevertheless, this is no actual discrepancy, as the theory deals with Z^{eff}, the charge effective in electronic interactions, while the experiments give the total charge e.

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Note added in proof.

A small improvement of the ionization chamber together with the use of argon instead of nitrogen in the chamber has made it possible in later experiments to distinguish clearly between the two groups of fission fragments and to determine the $H\varrho$-distribution curves for each of the two groups. In agreement with the previous results it was found that the two $H\varrho$-curves do not coincide, but that the abscissae of the curve for the light fragment are slightly, about 0.5×10^5 oersted $\times$ cm., higher than those of the curve for the heavy group. The most frequent values of $H\varrho$ for the light and heavy groups are found to be 6.7 and $6.0 \cdot 10^5$ oersted $\times$ cm., corresponding to e-values of 20 ε and 22 ε, respectively.

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