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TOTAL CHARGES AND ELECTRON CAPTURE CROSS-SECTIONS OF FISSION FRAGMENTS IN GASES

BY

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1. Introduction.

In the present paper the results of some older measurements are given, the publication of which for various reasons has been delayed a few years. In the meantime a theoretical paper by BOHR and LINDHARD[1)]—in the following cited as B. L.—has appeared, and since it affords a new basis for the treatment of the experimental results, a brief report of the latter seems appropriate.

2. Experimental Method.

As mentioned in a previous paper[2)] — in the following referred to as I — fission fragments have been deflected in a magnetic field, and from the curvature of the paths the total charges were estimated. Fig. 1, which shows the experimental arrangement, is reproduced from I. Fission fragments from a strip-formed, thin uranium layer (11) passed through a movable slit (12). Through a second slit (16) covered with a mica foil they entered an ionization chamber. The deflection chamber, i. e. the space between the uranium layer and the mica window, could be evacuated or filled with a gas to a low pressure. Records were made for various positions of the intermediate slit, and in this way the deflection distribution was obtained. From the pulse sizes it was possible to distinguish between the two groups of fragments. For further details the reader is referred to I.

Fig. 2 shows some deflection distributions obtained. When the deflection chamber is evacuated no change of charge takes place in it, and the deflections will be determined by the charges with which the fragments leave the surface of the uranium layer or any solid covering foil. The widths of the distributions give

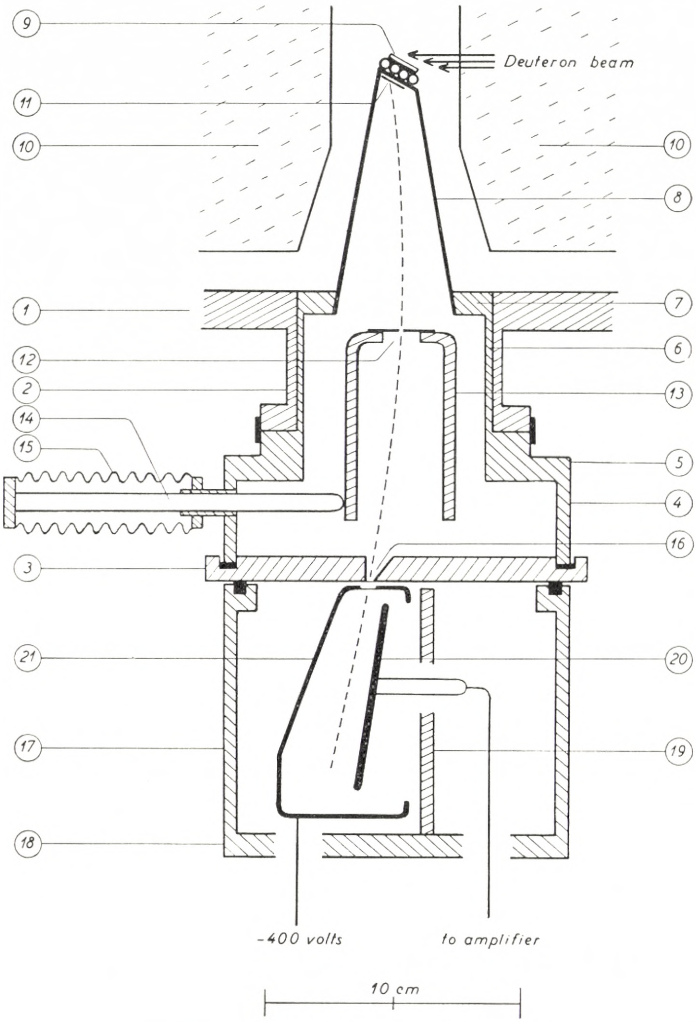

Fig. 1. Experimental apparatus.

information about the charge fluctuations in the solids. When a gas is admitted to the deflection chamber the fragments will, in collisions with the gas atoms, capture and lose electrons along the path, and rather quickly an equilibrium between loss and capture is established. The charge of each fragment will fluctuate around the average value, which will be reached close to the uranium layer if the gas pressure is high. In this case charge

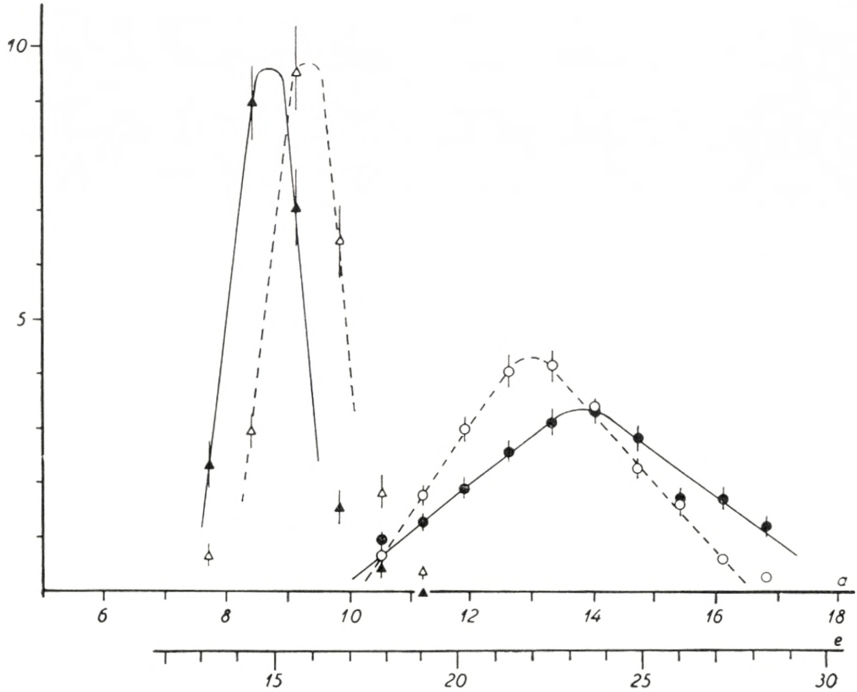

Fig. 2. Charge distributions for fission fragments. The abscissa a is the displacement of the middle slit in the deflection apparatus, given in mm. a is proportional to $\frac{e}{mv}$. Below is given the approximate charge scale (in units of the electronic charge) obtained by using the mean value for mv. Circles refer to fragments having traversed a thin *Be* layer and emerging into vacuum. Triangles refer to fragments emerging into argon at a pressure of 0.9 mm *Hg*. White and black points correspond to the light and heavy fragments, respectively.

exchanges will take place so frequently that the deflection will be determined almost solely by the average charge. The widths of the distributions obtained in this case are due mostly to the geometry of the apparatus. Of course, the gas pressure must not be so high as to cause appreciable stopping of the fragments inside the deflection chamber.

As illustrated by Fig. 2 the charges of fragments leaving solids were observed to be considerably higher than the equilibrium charges in gases. A fragment emerging into the gas will therefore start capturing electrons; if, however, the gas pressure is very low, the equilibrium charge will not be reached until a considerable part of the path in the deflection chamber is traversed. The distance travelled by the fragments before charge balance is obtained will be a function of the pressure. Accordingly, when the pressure increases from zero the deflection distribution gradually changes (see I, figs. 4—9). Fig. 3 shows the most probable deflections, i. e. the abscissae a for the peaks of the deflection curves, as functions of the argon pressure in the deflection chamber. Neglecting the width of the momentum

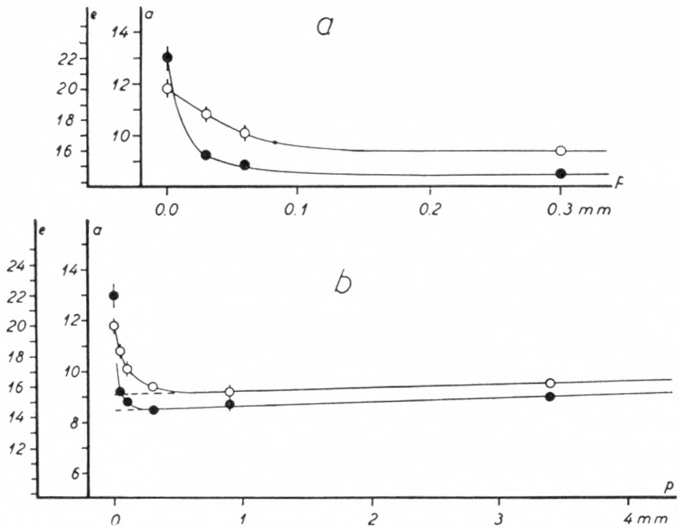

Fig. 3. Most frequent deflection a in mm plotted against the pressure of argon in mm Hg in the deflection chamber. Open and full circles refer to the light and heavy fragments, respectively.

distribution of the fragments, the deflections are proportional to the total charges e, the relation being $e = 1.70 \cdot a$, where e is measured in units of the electronic charge, and a in mm. The shape of the decreasing part of the curves for low pressures gives information about the rate of change of charge along the path and enables us to estimate the electron capture cross-sections of the fragments. Regarding the increase in charge for higher pressures, which illustrates the influence of excited states of the fragment ions on electron capture and loss cross-sections, the reader is referred to I (see also [3) 4)]) and to B. L., where a thorough discussion of these phenomena is given.

The estimation of the capture cross-section presents us with the following difficulties. Not only do the fragments capture electrons in collisions with the gas atoms, but they will of course also in some collisions lose electrons, even when their charges are higher than the equilibrium values. We can measure directly only the difference $\sigma_c - \sigma_l$ between capture and loss cross-sections, and the fact that both cross-sections may be expected to vary with the instantaneous fragment charge further complicates the phenomenon. However, from the fluctuation distributions in Fig. 2 (the right-hand curves) it follows that, for charge values a few units higher than the balance charge, σ_l is negligible as compared with σ_c. Hence, by simply disregarding the loss processes and assuming the capture cross-section to be nearly constant, a first approximation giving the order of magnitude of the average value of the latter could be obtained. Meanwhile, in § 4 of this paper a different method giving a somewhat more exact estimation will be described.

3. Experimental Results.

In I, deflection-pressure curves were given for A and H_2. Similar curves were later measured in He and N_2. Also, curves were measured in the various gases for slower fragments. In order to slow down the fragments a mica foil of thickness 0.47 mg per cm² was placed over the uranium layer. The fragments passed obliquely through the foil. Denoting by v_1 and v_2 the

TABLE 1.
Equilibrium charges of fission fragments.

	Light fragment		Heavy fragment	
	$v_1 \sim 6\, v_0$	$v_1' \sim 5\, v_0$	$v_2 \sim 4\, v_0$	$v_2' \sim 3\, v_0$
H_2	15.8	13.4	12.6	9.2
He	14.1	11.7	11.6	8.6
N_2	15.1	13.8	13.9	10.5
A	15.4	13.7	14.6	10.4
U	20.0		22.0	
Mica		19.4*		18.0*

* In *I* the charges for fragments leaving mica with reduced velocities were erroneously given as 18.8 and 17.2 instead of 19.2 and 17.8. The small differences between the latter figures and those given in the table are due to uncertainty in the zero position for the deflection scale.

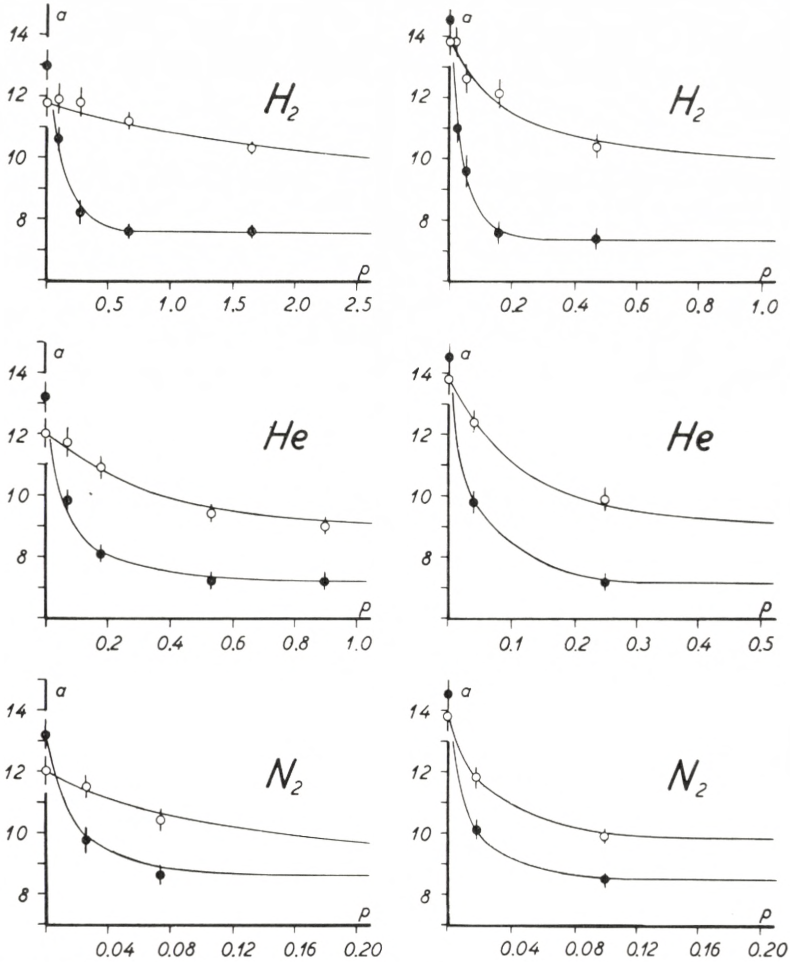

Fig. 4. Deflection vs. pressure curves in various gases. The curves to the left and right side refer to fragments with initial and reduced velocities, respectively. Open and full circles refer to the light and heavy fragments, respectively. The deflection is proportional to $\frac{e}{mv}$. Neglecting the momentum spread we have for fragments with full velocity, $e = 1.70 \cdot a$; for light and heavy fragments with reduced velocities, $e = 1.41 \cdot a$ and $e = 1.24 \cdot a$, respectively, a in mm, and e in units of the electronic charge.

initial velocities of the light and heavy fragments, respectively, and by v_1' and v_2' the velocities after their passage through the foil, one has

$$v_1' = 0.83 \cdot v_1$$
$$v_2' = 0.73 \cdot v_2.$$

The velocities thus happen to be close to 3, 4, 5 and 6 times v_0, the orbital velocity of the hydrogen electron. Fig. 4 gives the beginning of the curves for low pressures in the various gases. In all cases, at least two points corresponding to higher pressures were measured and from the latter points the equilibrium charges were determined. Table 1 summarizes the results. Within experimental errors the charge of the heavy fragment varies in all gases proportional to the velocity, in agreement with the approximative formula given by BOHR[5]), $e = Z^{1/3} \cdot \frac{v}{v_0}$, Z being the nuclear charge number of the fragment. The same applies to the light fragment in H_2 and He while, in the heavier gases, the charge of the light fragment varies more slowly with velocity. This result, however, is also in conformity with theoretical expectations, as discussed by BOHR and LINDHARD.

4. Calculation of the Effective Capture Cross-Section.

The derivation of the effective capture cross-section may be illustrated, taking as an example the case of the heavy fragment with reduced velocity in N_2. The theoretical estimates are obtained in the way described by BOHR and LINDHARD. For the capture cross-section we have the formula (B. L. (4.5))

$$\sigma_c = \pi a_0^2 e^2 z^{\frac{1}{3}} \left(\frac{v_0}{v}\right)^3,$$

where z is the atomic number of the stopping gas (here 7), a_0 and v_0 are the radius and orbital velocity of the hydrogen atom in the ground state, and v is the fragment velocity (here $3\ v_0$). In Fig. 5 σ_c is plotted against e. From the experiment the equilibrium charge is known to be 10.5 and, hence, for this abscissa $\sigma_l = \sigma_c$. Assuming σ_l to vary proportionally to e^{-3} (cf. B. L.), the curves for σ_l and $\sigma_c - \sigma_l$, respectively, are drawn. For $e = 18$, the mean charge with which the fragments enter the gas, we find $\sigma_c - \sigma_l = 21\ \pi a_0^2$.

Consider, next, the empirical estimation of $\sigma_c - \sigma_l$. For simplicity, all fragments are assumed to start with $e = 18$.

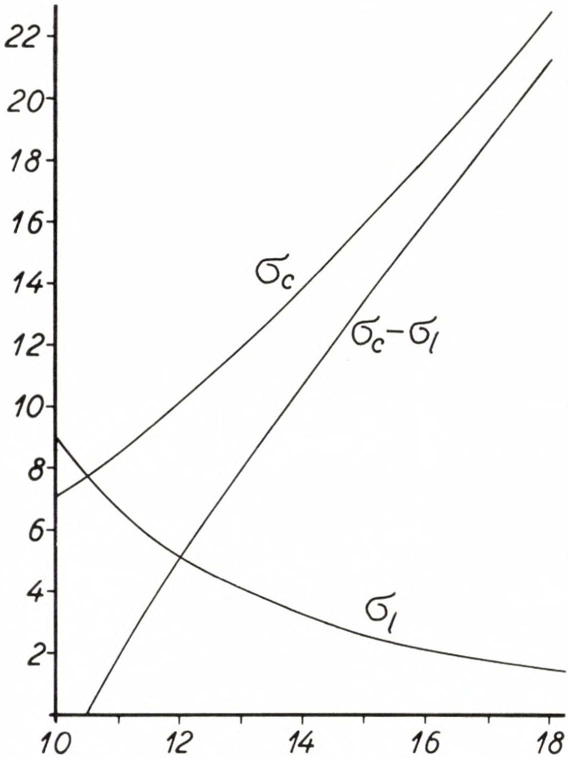

Fig. 5. Capture and loss cross-sections plotted against charge for the heavy fission fragments with $v = 3\,v_0$ in nitrogen at low pressure. Cross-section in units of πa_0^2, where $a_0 = \dfrac{\hbar}{m\varepsilon^2}$, and the charge in units of the electronic charge ε.

From Fig. 5 it is seen that the effective capture cross-section varies almost linearly with charge. Thus, we assume

$$\sigma_e = \sigma_{18}\frac{e - 10.5}{18 - 10.5}, \qquad e = 18, 17, \ldots,$$

the balance charge being 10.5, and σ_e denoting the effective capture cross-section for a fragment with charge e. Then, for the mean charge $\bar{e}\,(x)$ at a distance x from the uranium layer, we have (cf. B. L. (2.5))

$$\bar{e}\,(x) = 10.5 + 7.5\, e^{-\frac{1}{7.5}\sigma_{18} n x} = 10.5 + 7.5\, e^{-\frac{1}{7.5}\frac{x}{\lambda}},$$

TABLE 2.
Effective capture cross-section $\sigma_c - \sigma_l$ in units of πa_0^2.

Light fragment: $v \sim 6\,v_0$, $v \sim 5\,v_0$. Heavy fragment: $v \sim 4\,v_0$, $v \sim 3\,v_0$.

	$v \sim 6\,v_0$ exp.	$v \sim 6\,v_0$ th.	$v \sim 5\,v_0$ exp.	$v \sim 5\,v_0$ th.	$v \sim 4\,v_0$ exp.	$v \sim 4\,v_0$ th.	$v \sim 3\,v_0$ exp.	$v \sim 3\,v_0$ th.
H_2	0.06 ± 0.02	0.04	0.8 ± 0.3	0.13	1.6 ± 0.6	0.9	8 ± 2	3.5
He	0.7 ± 0.3	0.1	$4 \pm 2.$	0.55	9 ± 2	3.7	17 ± 5	15
N_2	1.4 ± 0.5	1.6	8 ± 4	2.7	15 ± 8	13	20 ± 6	21
A	2.5 ± 0.8	2.7		6	24 ± 8	18		30

where n is the number of atoms of the stopping gas per cm^3 and λ is a quantity which may be called the effective mean free path for electron capture by fragments with $e = 18$.

Suppose the gas pressure has such a value p_1 mm Hg that $\lambda = 10$ cm. The function $\bar{e}\,(x)$ may be calculated and, from the known variation of the magnetic field, the deflection of a fictitious fragment travelling with just the mean charge may be found by numerical integration. The deflection value so obtained is assumed to coincide with the peak for the actual deflection distribution, an assumption which is presumably not much in error. By calculating for various pressures, the whole deflection-pressure curve is obtained, the pressure being given in units of p_1. This curve is shown in Fig. 4, p_1 being chosen equal to 0.0008 mm Hg, which fits best with the experimental point. This value corresponds to $\sigma_{18} = 20\,\pi a_0^2$, a result which is in close agreement with the theoretical estimate.

In Table 2 are given the experimental results for $\sigma_c - \sigma_l$ in the various gases and for the different velocities, all estimates being based on the assumption that $\sigma_c - \sigma_l$ varies linearly with charge. The values corresponding to velocities 6 v_0, 5 v_0, 4 v_0, and 3 v_0 refer to charge values 20, 19.4, 22, and 18, respectively. For comparison are given theoretical values, kindly estimated by Mr. J. LINDHARD in the way described in B.L. The agreement is satisfactory for the values referring to nitrogen and argon, whereas, in the lighter gases most of the experimental values are rather high as compared with the theoretically computed figures. Since the cross-sections are small in the lighter gases, it is clear that possible impurities in the latter would just tend to increase the cross-sections. However, great care was taken to avoid impurities; before the experiments the deflection chamber was always filled three times and evacuated carefully between the fillings; during the experiments the chamber was connected to a liquid air trap in order to remove vapors. The tank helium was known to contain three per cent nitrogen, but it was slowly filtered through charcoal in liquid air and should thus be very pure. The tank hydrogen was said to contain less than 0.1 per cent impurities. Also, the small experimental value obtained for $\sigma_c - \sigma_l$ of the light fragment with $v = 6\, v_0$ in H_2 seems to show, quite apart from the good agreement with the theoretical figure, that the possible impurities are much too small to influence essentially the other values for $\sigma_c - \sigma_l$ in hydrogen. As seen, the experiments indicate for the light fragment in H_2 a very strong velocity dependence of the effective capture cross-section. In *He* $\sigma_c - \sigma_l$ is found experimentally to be considerably higher than the theoretical estimate, as well for $v = 6\, v_0$ as for $v = 5\, v_0$, whereas the ratio between the cross-sections corresponding to the two velocities is in agreement with the theory. For the heavy fragment, in H_2 and in *He*, the differences between experimental and theoretical values are less pronounced.

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References.

1) N. Bohr and J. Lindhard: Dan. Mat. Fys. Medd. **28**, no. 7, 1954. In the paper referred to as B.L.
2) N. O. Lassen: Dan. Mat. Fys. Medd. **26**, no. 5, 1951. In the paper referred to as I.
3) — Dan. Mat. Fys. Medd. **26**, no. 12, 1951.
4) — Thesis. On The Total Charges and The Ionizing Power of Fission Fragments. Munksgaards Forlag, Copenhagen 1952.
5) N. Bohr: Dan. Mat. Fys. Medd. **18**, no. 8, 1948.

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