Scattering and Stopping of Fission Fragments

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THE cloud-chamber pictures of tracks of uranium fission fragments in gases obtained by Brostrøm, Bøggild and Lauritsen[1] have revealed a number of interesting differences between such tracks and those of protons and alpha-particles. These differences may be simply shown to be caused by the comparatively high charge and mass of the fission fragments, which imply that nuclear collisions play a much greater part in the phenomenon than is the case for the ordinary light particles.

For such particles as protons and α-particles, measurable scattering in nuclear collision is comparatively rare, and practically all the stopping is caused by the interaction between the particles and the electrons in the gas atoms. For the fission tracks not only are branches due to close nuclear collisions the rule rather than the exception, but also the scattering and stopping effect of numerous less violent collisions is clearly shown in the irregular gradual bending of the tracks as well as in the peculiar form of the range velocity curve. Moreover, the contribution by the electrons to the stopping is greatly reduced by the fact that the fission fragments during their entire range will carry with them a large number of bound electrons, which, without essentially affecting the nuclear collisions, will in large part neutralize the effective charge of the fragments in electron collisions.

The continual capture and loss of electrons by the high speed fragments is a rather complex phenomenon, but, to a first approximation, we may assume that the fragment will possess an average effective charge equal to the ratio of its velocity V to the "orbital" velocity $V_0 \sim 10^8$ cm/sec. of the least tightly bound electron in the neutral atom. Since the orbital velocity of any electron is roughly proportional to the effective nuclear charge in the region concerned of the atom, this follows, in fact, if we assume that all the electrons carried with the fragment will have orbital velocities greater than or equal to V.

In an encounter between the fragment and a heavy atom possessing electrons lightly bound and also electrons with velocities greater than V, we may, moreover, assume that only the former electrons, in approximate number V/V_0, will be effective in the stopping. This is true since the faster electrons, just as the electrons carried with the fragment, will be merely adiabatically influenced during the encounter and will therefore have no retarding effect.

The calculation of the stopping power under such conditions, is particularly simple since, because of the comparatively high effective atomic charges, classical mechanics can be directly applied in calculating the energy and momentum transfer during the collisions. Using the above estimates of the effective charges and denoting by μ and ϵ the mass and charge of the electron, we get for the average rate of velocity loss for the fragment of mass M and charge number Z in a gas with N atoms per unit volume, each with nuclear mass m and charge number z,

$$\frac{dV}{dx}=\frac{4\pi\epsilon^4 N}{M\mu V_0^3}\left\{\ln\left(\frac{V}{V_0}\right)^2+\frac{Z^2z^2\mu(M+m)}{Mm}\left(\frac{V_0}{V}\right)^3 \times\ln\left[\frac{Mm(Z+z)}{\mu(M+m)Z^2z^2}\left(\frac{V}{V_0}\right)^2\right]\right\}, \quad (1)$$

where the first term in the bracket originates from electronic interaction, while the second is due to direct nuclear collisions.

In the case of a fission fragment of mass and charge numbers 140 and 50, traveling through argon gas with mass and charge numbers 40 and 18, the constant factor before the logarithm in the second term is about 10. This term, which, for the initial part of the range, where the velocity is about $20V_0$, is much smaller than the first term, will thus be the greater near the end of the range when the velocity has fallen to

[1] K. J. Brostrøm, J. K. Bøggild, T. Lauritsen, preceding paper.

about $2V_0$. From formula (1), we shall therefore expect the range-velocity curve to have essentially different features at the beginning and at the end of the range. Neglecting the slow variation of the logarithms, we shall, in fact, expect the rate of velocity decrease to be practically linear at the beginning of the range and to vary as the inverse cube of the velocity at the end of the range.

A curve of just this character would seem to fit the experimental data and the agreement would seem to be quite satisfactory also in a quantitative respect. For a comparison between theory and experiment at the very end of the range, it is essential to note that it is a condition for the approximation concerned that the arguments of the logarithms in both terms are greater than 1. While this means that the first term can be used only for $V > V_0$, the second term will hold with some approximation even for $V < V_0$, since the constant factor in the logarithm argument will be about 10.

Since, according to (1), the rate of velocity loss is, in the major part of the range, independent of Z, and inversely proportional to M, it follows further that two highly charged nuclei with the same initial momentum will have approximately equal ranges. This fits in well with the experimental finding that the tracks of the two fragments resulting from a single fission process in a thin uranium target have nearly the same length, although their masses and charges should in general differ considerably. In this connection, it may also be noted that, because of the preponderant effect of the nuclear collisions in the end part of the range, one should expect a straggling far greater than for protons and α-particles. While for light particles, the mean square value of the fractional straggling in range is of the same order of magnitude as the ratio of the mass of the stopping electrons to that of the moving particle,[2] we shall, in fact, expect that this value will be of the order of m/M for a considerable part of the range of fission particles.

Furthermore, the characteristic curving of the fragment tracks revealed by the cloud-chamber pictures can be shown to be a simple consequence of the scattering effect of the numerous nuclear collisions too small to give rise to detectable branching. In fact, it is easily shown that the mean square of the deviation in angle within a part of the range where the energy is changed by ΔE is given by

$$\Phi^2 = \frac{m}{M} \cdot \frac{\Delta E}{E} \left[\frac{\Delta_N E}{\Delta_N E + \Delta_e E} \right], \tag{2}$$

where $\Delta_N E$ and $\Delta_e E$ are the fractional contributions to ΔE of the nuclear and electronic collisions respectively. While the bracketed term is small in the beginning of the range, it is, near the end of the range, almost equal to 1, and here, where the bending is easily measurable, formula (2) agrees quite satisfactorily with the experiments.

The calculations here indicated will be given in greater detail in a paper to be published in the *Communications of the Copenhagen Academy of Science.*

[2] N. Bohr, Phil. Mag. **30**, 581 (1915).