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TWO TYPES OF FISSION AND THE NUCLEAR CHARGE DISTRIBUTION

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The results of previous studies of partial fission yields are analyzed by taking into account new data pertaining to the emission of prompt neutrons. It is noted that symptoms of the existence of two independent fission modes can be discerned in the charge distribution as well as in the mass and fragment kinetic energy distribution.

RECENT investigations of the kinetic energies of fission fragments with different masses [1,2] have shown that the consideration of the mass distributions as being superpositions of two types of fission—symmetrical and asymmetrical—is not a purely formal procedure. It was established that each fission method has its own special kinetic characteristics. In certain fragment-mass regions superposition of the two types of fission is expected and is clearly manifest in the distribution of the kinetic energies, for example, in the broadening (and even the occurrence of double tops) of the curve of fission probability vs. energy of the paired fragments for a given mass ratio (1.1—1.3 in the case of Th^{232} and U^{238} fission). In addition, a comparison of the properties of the fission methods considered enables us to conclude [2] that symmetrical fission is a "faster" process and asymmetrical a "slower" one, requiring some time for the formation of the shells in the resultant fragments.

It is natural to examine from this point of view other characteristics of the fission process, too. We can note, in particular, some differences in the properties of neutron emission, viz., the total number of neutrons evaporated from the symmetrical-fission [3] fragments increases and the character of the dependence of the number ν of neutrons emitted for an individual fragment on the mass A of this fragment changes [4]. As already noted [4], ν increases with increasing A of both the heavy and light fragments only in the region of asymmetrical fission, not in symmetrical or highly asymmetrical fission. It seems probable that in symmetrical fission the total number of neutrons should be distributed among the paired fragments in accordance with the usual notions of the statistical model, that is, in proportion to the fragment masses.

In the present paper we attempt to analyze the available data on the distribution of the charge of the fissioning nucleus among the fragments. The results of the earlier works had to be reviewed here to take into consideration the new data on prompt neutrons [3,4].

As is well known, the charge distribution can be described with the aid of two parameters—the most probable charge Z_p for a fragment with mass A, $Z_p(A)$, and a parameter C, which characterizes the half-width of the distribution, which is assumed to have the Gaussian form

$$y = (C\pi)^{-1/2} \exp\{-(Z - Z_p)^2/C\}.$$

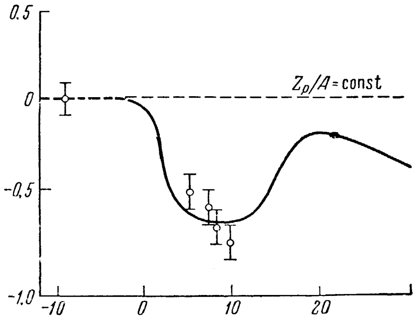
The most complete and direct data on Z_p were recently published by Wahl et al [5] for the low-energy fission (thermal and spontaneous) with a direct determination of Z_p made for six chains each with two and more independent yields. (The fact that Z_p was obtained directly from the experimental data is particularly important in our case.) The results of the determination are given in the figure in the form used in [5]. It is seen from the figure that in the region of masses with large yield, the most probable fragment charge differs greatly from the value expected if the charge ratio remains constant (when $Z_p/A = Z_c/A = \text{const}$; Z_c and A_c are the charge and mass of the fissioning nucleus). At the same time, in the region where the yields fall sharply for all the heavy nuclei ($A \approx 132$ for the heavy fragment), a radical change occurs also in the value of Z_p, so that Z_p approaches the values calculated for a constant charge ratio.

Wahl et al [5] connect this decrease with the closeness of the proton shell ($Z = 50$) and advance the hypothesis that the observed yields in the valley of the mass curve are due essentially to beta decay of the products, other than the primary fragments with $Z = 50$. This would mean a sharp asymmetry in the charges of the fragments of approximately equal mass, and should lead to a reduction of the Q of the reaction. However, as shown in recent investigations by Apalin et al [3], no reduction occurs in Q for symmetrical fission —the decrease in the kinetic energy is offset by the increase in the number of neutrons.

It can be assumed, however, that when $A \approx 132$ a transition occurs from asymmetrical fission to symmetrical fission. This follows from the sharp decrease in the yields in this region and from the data on the kinetic energies of the fragments [2]. The symmetrical fission method is apparently characterized by a different charge distribution. Indeed, it can be readily assumed that for symmetrical fission the charge distribution should satisfy the rule $Z_p/A = \text{const}$, since it has been shown earlier that this process is "fast."

The cross section for the production of fragments which are approximately symmetrical in mass is very small in low-energy fission. It is therefore natural for further analysis to turn to fission with high excitation energy. We have used the independent yields determined in experiments on fission of U^{235} by 14-MeV neutrons [6,7]. It is assumed that in such excitations the character of the charge distribution still remains the same (just as the mass distribution still remains asymmetrical), that is, the Z_p of the primary products is determined by the same empirical relation as in low-energy fission [8], but a certain broadening of the curve can occur, owing to the increase in the internal energy of the fragment excitation. (The latter follows from the fact that the kinetic energy of the asymmetrical-fission fragments is almost independent of the energy of the particles that induce the fission.)

For low-energy fission we obtain $C = 0.94$ [5], and in our case we assume $C = 1.3$. In good agreement with this value of C and with the values of Z_p indicated in the figure are the experimentally obtained yields of I^{132}, I^{134}, Cs^{136}, and Nb^{97}, but the calculated yield of Ag^{112} is twice as large as the experimental value 5.1 ± 0.7 per cent. In the calculation for $A = 112$ we assumed $\nu = 4$, that is, approximately half the number of neutrons emitted in symmetrical fission [3]. To reconcile the particular yield of Ag^{112} with the obtained value it was necessary to assume that in this case $C = 0.9$. From the point of view of the hypothetical existence of two fission methods (and accordingly, two charge distributions), the last result is not surprising, since the nuclei I^{132}, I^{134}, Cs^{136}, and Nb^{97} are obtained by asymmetrical fission of the nucleus, while Ag^{112} is obtained by symmetrical fission. One could expect the charge distribution for symmetrical fission of heavy nuclei to be narrower than for asymmetrical one, since the charge distribution turns out to be narrower in the symetrical fission of Au^{197} by 112-MeV C^{12} ions [9], than in the asymmetrical fission of heavy elements at the same excitation energy [10].



Most probable charge of primary fragments (the ordinates are the quantities $Z_{p.h} - A'_h Z_c/A_c = A'_l Z_c/A_c - Z_{p.l}$, while the abscissas represent $A'_h - 50A_c/Z_c = A_c(1 - 50/Z_c) - A'_l$, where the subscripts "$l$" and "h" denote the most probable charge and primary mass of the light and heavy fragments, respectively). The continuous line is the empirical value of Z_p for low-energy fission[5], o – values of Z_p for fission of U^{235} by 14.5-MeV neutrons[6,7], dashed line – Z_p for a constant charge ratio.

It is interesting to note that the experimental variation obtained for $Au^{197} + C^{12}$ (112 MeV) agrees best with the hypothesis of minimum potential energy and does not deviate much from the results of the $Z_p/A = \text{const}$ rule, thus confirming the "fastness" of the symmetrical-fission process. For "fast" fission the variance of the charges ΔZ_A at constant A can be related with the variance of the masses ΔA_x at constant Z by the simple relation

$$\Delta A_Z = (A/Z)\,\Delta Z_A.$$

This relation is indeed in agreement with experiment: Blann [9] found that the A-distribution for given Z is Gaussian with $C = 6$, while for the Z-distribution for given A $C = 0.9$; consequently, the ratio of the variances is $(6/0.9)^{1/2} = 2.57$, which agrees within the limits of the experimental error (~10%) with the A/Z of the fissioning nucleus.

It must be assumed that only symptoms of an occurrence of two charge distributions, each with its own Z_p and C, have been found at present. There is still very little known concerning the values of Z_p and C for symmetrical fission (in light and heavy nuclei), or concerning the dependence of these parameters on the excitation energies (for both types of fission). It is of interest to make a detailed comparison of the charge distributions for symmetrical and asymmetrical fission of heavy nuclei (for example Th and U) at excitation energies 30—50 MeV, when both methods of fission manifest themselves with noticeable probability. In this case, at fragment-mass ratios 1.1—1.3, when both types of fission are present, one can expect that their superposition will result in a double-peaked (or simply broader) charge distribution.

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