KINETIC ENERGY OF FRAGMENTS EMITTED IN SUB-BARRIER FISSION

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We have analyzed experimental data comparing kinetic energy distribution in spontaneous and induced fission of the compound nuclei U^{238} and Pu^{240}.[1-4] These data, together with measurements reported in the present work, indicate that the kinetic energy E_k in sub-barrier fission is lower than in super-barrier fission; the effect is larger than the experimental error. This conclusion is supported by the data on the number of secondary neutrons emitted per fission event. A semiquantitative interpretation of the effect and its dependence on nuclear charge is given on the basis of energy balance considerations. The results of this work indicate the need of refining Terrell's scheme for systematizing E_k[12] by considering the data on spontaneous and induced fission separately.

UNTIL recently, the most precise information giving the mean kinetic energy of fission fragments E_k as a function of the excitation energy of the fissioning nucleus E_x was obtained by analyzing the mean number of prompt neutrons emitted in a fission event ν. These data do not contradict the Fowler hypothesis that E_k is independent of excitation energy. A direct experiment reported recently[1] shows that the mean kinetic energies of the fragments in thermal fission and in fission by neutrons with mean energies of 5 MeV are the same to within 0.1%. This result is in agreement with the existing picture that the kinetic energy of the fragments is determined primarily by the Coulomb repulsion energy at rupture of the neck of the fissioning nucleus.

In a discussion of the dependence of ν on the type of nucleus[2] attention was directed to the fact that the experimental values for nuclei with $Z < 94$ are considerably higher than the values obtained by extrapolation of the Fowler hypothesis into the sub-barrier region of excitation energy for the compound nucleus. The difference in these values for U^{238}, the nucleus with the smallest Z for which ν has been measured in spontaneous fission, is 0.5.[2] It was noted[2] that this effect can be understood if one allows E_k to increase in going from spontaneous fission to induced fission in U^{238}; this can be easily established qualitatively from a consideration of the results of Petrzhak, Kovrigin, and Kondrat'ko.[3,4] A similar displacement of the distribution of kinetic energy of a fragment pair toward lower energy in spontaneous fission of Pu^{240} as compared with the distribution of E_k in thermal fission of Pu^{239} has been observed by Mostovoĭ.[5] This displacement also corresponds to a difference in the mean growth of the quantity $\nu(d\nu/dE)$ in the super-barrier and sub-barrier fission regions of the compound nucleus Pu^{240}.[6]

The difference in kinetic energy in spontaneous and induced fission in the same nucleus can be understood qualitatively from an analysis of the potential energy curve plotted as a function of the deformation parameter. The kinetic energy in spontaneous fission is approximately equal to the difference between the potential energy at the time the fragments escape from the barrier zone and the potential energy of the fragments at large distances. In super-barrier fission this same quantity is evidently supplemented by the kinetic energy of the relative motion acquired by the fragments in reaching the top of the barrier, that is, the energy they acquire before becoming free. Andreev[6] assumes that part of the potential energy corresponding to the quasi-static stage of emission from the barrier top goes into the degree of freedom associated with the kinetic energy of the relative motion of the fragments; Geĭlikman has shown[7] that in this stage the excitation of the nucleon degrees of freedom is small.

In order to obtain some kind of a quantitative relation between the magnitudes of the mean kinetic energy of the fragments in spontaneous and induced fission we have analyzed the results reported in [3-5] and [8]. In the work of Petrzhak, Kovrigin, and Kondrat'ko[3,4] the distributions of E_k in spontaneous fission and photofission of U^{238} were compared with the corresponding data for thermal fission of U^{235}. The kinetic energies for spontaneous fission of U^{238} and induced fission of U^{235} have also been compared by Whitehouse and

Compared nuclei and fission mode	Difference in kinetic energy E_k, MeV	Difference in number of prompt neutrons	Computed value $\Delta E_k = \Delta\nu / \frac{d\nu}{dE}$, MeV
Fission (Pu^{239} + n) and spontaneous fission of Pu^{240}	1.5±0.5 [5]	0.2 [6]	1.4
Fission (U^{235} + n) and spontaneous fission of U^{238}	3.5±1 [8] 4.0±0.7 [3]	—	—
Fission $U^{238} + \gamma$ and U^{235} + n	1.0±0.7 (Our work)	—	—
Fission $U^{238} + \gamma$ and spontaneous fission of U^{238}	4.8±1.0 (Present data)	0.5 [9]	3.6

Galbraith.[8] Since the accuracy of the measurements reported in [4] was extremely poor we have carried out an additional experiment in which the mean kinetic energies for photofission of U^{238} and thermal fission of U^{235} could be measured with higher accuracy. The source of 7-MeV gamma rays was the reaction $F^{19}(p, \alpha, \gamma)O^{16}$. In analyzing the experimental data we made corrections for variations in layer loss due to the anisotropic distribution of fragments in photofission of U^{238}.[9]

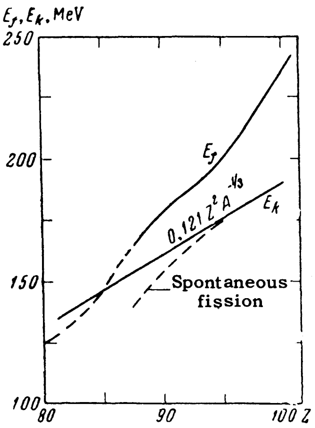
In the table we show the results of an analysis of the data of the work mentioned above and show $\Delta\nu$, the difference between the experimental values for spontaneous fission of Pu^{240} and U^{238}, and the corresponding quantities obtained by extrapolation of a linear relation $\nu(E_x)$ into the sub-barrier region. The value $\Delta E_k = \Delta\nu/(d\nu/dE)$ computed from the difference in $\Delta\nu$ in accordance with the energy balance equation for fission should correspond to the measured value. The errors in the measurements of the mean kinetic energy E_k given in the table, which have an experimental distribution $F(E_k')$, were computed from the formula

$$\sigma = \sqrt{\int (E_k' - E_k)^2 F(E_k')\, dE_k'} \Big/ \int F(E_k') dE'_k.$$

It is evident from the table that the measured difference ΔE_k for spontaneous and induced fission is appreciably larger than the limits of experimental error and is in good agreement with the data on ν. If the reduction in kinetic energy in going from super-barrier fission to sub-barrier fission were due completely to the variation in kinetic energy of the relative motion at rupture one would expect higher values of ΔE_k to be associated with higher values of Z^2/A because in this case the deformation at the saddle point is reduced while the nuclear configuration at rupture remains approximately the same.[10] Analysis of the experimental data carried out in the present work shows an opposite dependence on Z^2/A for U^{238} and Pu^{240}. This does not necessarily mean the failure of the ideas given above but may be the result of some other effect.

It has been shown by Geĭlikman[7] that the excitation energy in spontaneous fission, which is directly related to the deformation of the fragments at separation, is weakly dependent on Z^2/A (for example, in going from U to Cf); this energy is approximately 24 MeV. This feature can be understood as the result of the weak dependence of the configuration at the instant of separation indicated above (and the associated weak dependence of excitation energy) on A and Z. This means that the fission process must occur in such a way that the amount of excitation energy indicated above can be realized.

In the figure we show the mean kinetic energy and the total energy Ef in spontaneous fission as functions of Z. The curve of total fission energy



The fission energy E_f and the kinetic energy E_k as functions of nuclear charge Z computed for isotopes with maximum stability against β-decay from the liquid drop model. The choice of nuclei with fixed values of A, associated in a definite way with the charge Z, has been made in order to avoid small and unimportant (for the purposes of the present analysis) variations of E_f and E_k as functions of A. The dashed line shows the dependence of E_k on Z for spontaneous fission. The initial segment of the curve E_f is not reliable (dashed) since the most probable channel for fission in these nuclei is not known.

is plotted for the most probable fission channel as determined by the calculated values of the nuclear masses.[11] The curve $E_k(Z)$ is plotted in accordance with the Terrell scheme ($E_k = 0.121 Z^2A^{-1/3}$ MeV) and is based on the data for induced ($Z \le 94$) and spontaneous ($Z \ge 94$) fission. It is evident from the figure that the quantity $E_f - E_k$ diminishes as Z is reduced and that it vanishes when $Z \approx 85$.

It follows from the considerations given above that if the Terrell scheme[12] is used, then a reduction in nuclear charge in spontaneous fission means that the deficit of excitation energy is increased markedly, reaching approximately 3 MeV even at U. This difference is still greater for nuclei with smaller values of Z. From this pattern we draw the following conclusion: the requirement that spontaneous fission in nuclei with $Z \le 94$ occur with minimum excitation energy must, from energy balance considerations, lead to a reduction in the kinetic energy of the fragments. This means that the actual rupture and "liberation" of the fragments of the fissioning nucleus in spontaneous fission in these nuclei will occur at greater distances than for induced fission in the same nuclei. In the figure, the dashed line shows the curve $E_k(Z) = E_f - 24$ MeV which, as a first approximation, may be identified with the E_k curve for spontaneous fission. It should be noted that this curve is in agreement with the experimental data for U^{238} and Pu^{240}. However, it must be kept in mind, that the quantity ΔE_k evidently represents the resultant of the effects of two factors that tend to reduce the kinetic energy of the fission fragments in spontaneous fission: the reduction in energy of relative motion at the moment of separation and the deficit in the excitation energy. It can be shown that small changes in the distribution of fragment masses observed in experiments do not explain the ΔE_k effect.

Within the framework of the explanation proposed here for the dependence of ΔE_k on Z it can be shown that the number of prompt neutrons in spontaneous fission for nuclei with $Z \le 94$ remains constant and equal to $(E_f - E_k - E_\gamma)d\nu/dE \approx 2$. In this sense the extrapolation of the data on ν for induced fission to spontaneous fission for those nuclei used in [2] is evidently not valid. It also follows from the features of spontaneous fission for nuclei with $Z \le 94$ discussed here that the rapid reduction in the probability of spontaneous fission with a reduction in Z, which is not in satisfactory agreement with the relatively weak change in the height of the barrier, can just as easily be attributed to an increase in the effective width of the barrier.

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315