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Mass and Energy Distributions from 77.3-MeV-^{4}He-Induced Fission of ^{181}Ta, ^{209}Bi, and ^{233}U: A Test of Liquid-Drop-Model Predictions*

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Thin targets of ^{181}Ta, ^{209}Bi, and ^{233}U have been bombarded with 77.3-MeV ^{4}He ions at the Oak Ridge isochronous cyclotron. Correlated measurements of kinetic energies of fission-fragment pairs have been made, and mass and total kinetic energy distributions were obtained. The widths of the distributions were compared with predictions of the liquid-drop model for fission. The trends predicted by theory were observed, but the absolute magnitude of the distribution widths were not in agreement with liquid-drop-model predictions. It is concluded that the liquid-drop model describes fission of relatively light nuclei in general terms, but that it should not be used in those cases where accurate quantitative predictions are required.

The first attempt to construct a theory describing the division of a nucleus from initial conditions to final observed fragment distributions was made by Nix and Swiatecki[1] in 1965. They used an approximate version of the liquid-drop model in which the fissioning nuclei were described by combinations of spheroidal shapes and the fragment nuclei by spheroids. Within this framework, by following dynamic as well as static properties of the system, they calculated distributions of fragment mass, kinetic energy, and other variables. Experiments designed to compare with the theory gave generally good agreement for fissioning nuclei lighter than radium.[2]

Later, Nix refined the theory by including a hyperbolic neck connecting the two spheroidal fragments before scission.[3] This parametrization gave more realistic saddle-point shapes, and also gave generally good agreement with the earlier experiments on lighter fissioning nuclei.

In recent years, beginning with calculations by Strutinsky,[4] it has been shown that single-particle and shell effects are important in fission,[4-7] and, indeed, that they give rise to a double barrier for fission in the actinide region. In the case of lighter nuclei ($A \lesssim 220$), shell effects have been shown to influence the potential-energy surface rather strongly, in such a manner that the saddle point is shifted towards smaller elongation and less constriction relative to the liquid-drop-model prediction; however, the minimum-potential-energy path to scission for the lighter nuclei appears not to be significantly different in the two cases, in spite of the relatively strong shell influences.[7] It remains possible therefore, that the liquid-drop model could provide a useful framework for calculating the fission properties of nuclei lighter than radium, even though some deviations due to shell effects might be expected.

The purpose of the present experiment was to examine one specific prediction of the Nix theory at moderate excitation energies, where the theory predicts mass distributions from the fission of lighter nuclei to be broader than those from the fission of heavier nuclei, while the total kinetic energy distributions for the lighter nuclei are predicted to be narrower than for the heavier fissioning nuclei. The requirements for a test of these predictions are: (1) The systems compared must span as broad a range in mass of the fissioning nuclei as possible; (2) the excitation energy (and hence the nuclear temperature) should be about the same for all cases; and (3) only distributions peaked at symmetric mass division can be considered. To satisfy these conditions, ^{181}Ta, ^{209}Bi, and ^{233}U were bombarded at the Oak Ridge isochronous cyclotron with 77.3-MeV ^{4}He ions. The compound nuclei formed are ^{185}Re, ^{213}At, and ^{237}Pu, respectively. Fragment-energy correlation measurements were made using methods discussed in earlier papers (see, for example, Refs. 2 and 8). The kinetic energies obtained in such experiments are post-neutron-emission energies, while the masses obtained are the provisional masses of Schmitt, Neiler, and Walter,[8] and closely approximate pre-neutron-emission masses.

The targets consisted of thin evaporated deposits (about 50 μg/cm^2) on 5-μin. nickel backings. The data were corrected for the effect of finite target and backing thickness. A multiparameter analyzer was used to store correlated pulse-height information. To minimize pileup effects, the beam current was kept below 100 nA and was held constant for all three cases investigated. No neutron corrections were applied to the data. The measured distributions are shown in Fig. 1.

A knowledge of the nuclear temperature θ is required to obtain the appropriate theoretical distribution width for any specific case. The temperature was estimated from the relationship $E_x = a\theta^2 - \theta$, where E_x is the known compound-nucleus excitation energy and a is the level-density parameter, assumed for our purpose to be equal to $\frac{1}{8}A$ (A is the compound-nucleus mass). A complication in the evaluation of θ stemmed from the possibility of fission occurring after neutron emission from the compound nucleus. From measured excitation functions[9] it was possible, in the case of ^{181}Ta and ^{209}Bi, to obtain average excitation energies. One value of the nuclear temperature, θ_1, was evaluated on the assumption that all fission takes place before neutron emission, and another value, θ_2, was obtained on the assumption that all fission takes place at the estimated average excitation energy.

Table I is a summary of experimental and theoretical distribution widths. It can be seen that differences between theoretical values of the full width at half maximum (FWHM) based on the two different assumptions involved in calculating the nuclear temperatures θ_1 and θ_2 are not large. In the case of ^{233}U it was not possible to estimate the average excitation energy, and thus theoretical values are given only for first-chance fission. Table I also gives theoretical and experimental values of the average total kinetic energy. Our results are consistent with earlier observations[3] that total kinetic energies predicted by the liquid-drop model are systematically too low. Figure 2 shows the experimental FWHM results together with theoretical results from Ref. 3 as a function of the fissility parameter x.[10] The shaded areas represent the regions in which the experimental results were expected to fall. In all cases, the measured distributions are broader than expected. The width of the ^{233}U(^{4}He,f) mass distribution is more than double the predicted width. It is probable that this large width is due to a substantial component of asymmetric fission.

The presence of a large asymmetric-fission component in the ^{233}U case is probably caused by one or both of the following effects. First, since

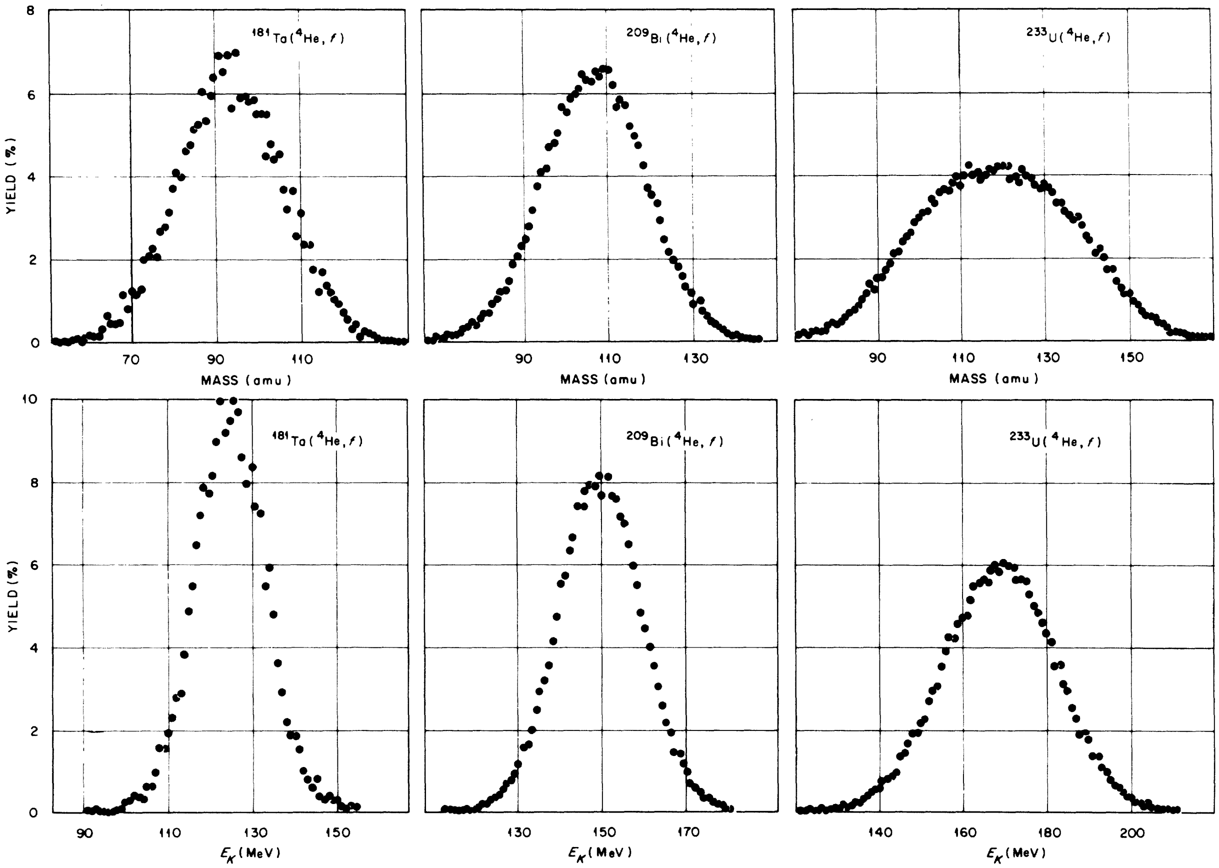

FIG. 1. Percentage yield as a function of fragment mass and total fragment kinetic energy E_K for various targets bombarded with 77.3-MeV ^{4}He ions.

TABLE I. Experimental and theoretical widths (full widths at half maximum) of mass (A_1) and total kinetic energy (E_K) distributions. The ^{4}He bombarding energy was 77.3 MeV. The theoretical numbers are from the work of Nix (Ref. 3). x is the fissility parameter (Ref. 10). The nuclear temperature θ_1 is calculated on the assumption that all fission takes place before the emission of neutrons from the compound nucleus. Temperature θ_2 is a calculated average temperature at which compound nuclei fission; it is estimated by means of measured excitation functions (Ref. 9). Also shown are the calculated and experimental values of average total kinetic energy.

	^{181}Ta target	^{209}Bi target	^{233}U target
x	0.6383	0.7189	0.7932
θ_1(1st chance) (MeV)	1.46	1.37	1.48
θ_2(average) (MeV)	1.41	1.23	
FWHM(A_1) (amu)			
Calculated for θ_1	26.6	20.6	20.1
Calculated for θ_2	26.4	19.5	
Experiment	29.3	28.7	49.0
FWHM(E_K) (MeV)			
Calculated for θ_1	15.5	16.7	19.8
Calculated for θ_2	15.3	16.1	
Experiment	19.9	23.3	31.0
Average total kinetic energy (MeV)			
Calculated	117.1	138.5	165.0
Experiment	124.8	149.2	168.6

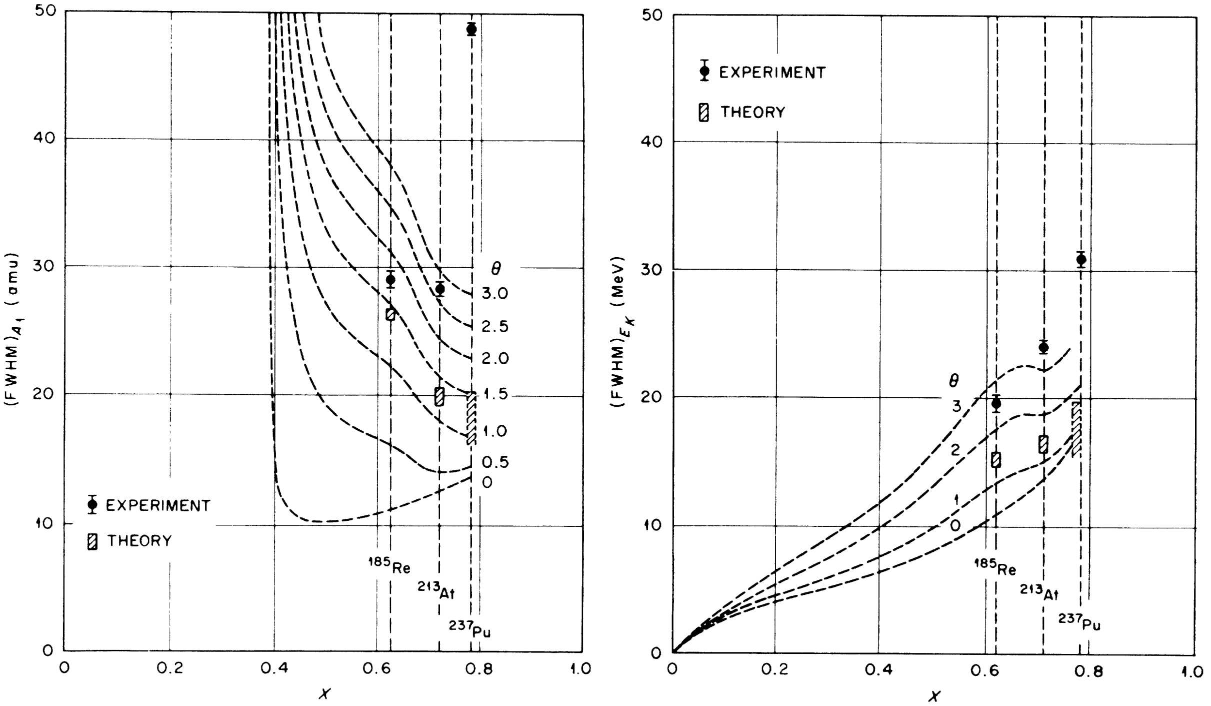

FIG. 2. Experimental and theoretical widths (full widths at half maximum) of mass (A_1) and total kinetic energy (E_K) distributions as a function of the fissility parameter x. The dashed curves at various values of nuclear temperature θ are from the work of Nix (Ref. 3). The shaded areas indicate the regions where experimental points were expected to fall. The size of the shaded area reflects the uncertainty in the nuclear temperature of the fissioning nucleus.

the fission probability is very high and fission can occur following the emission of several neutrons, the observed distribution probably results from a broad mixture of compound-nucleus excitation energies. Fission at lower excitation energies has a greater asymmetric-fission component. Second, single-particle effects, which are thought to dominate the fission process for the actinide nuclei at low excitation energies, do not disappear with increased excitation energy as rapidly as might have been expected, and an asymmetric-fission component may be present in our distribution due to persisting single-particle effects even at our relatively high excitation energy.

Restricting our attention to the compound nuclei ^{185}Re and ^{213}At, we see that, as predicted, the width of the mass distribution is broader in the ^{185}Re case, while the total kinetic energy distribution is broader in the ^{213}At case. While the difference between the FWHM of mass distributions from ^{185}Re and ^{213}At is predicted to be quite large (~6.5 amu), the observed difference is small (~1 amu). On the other hand, the predicted difference of only ~1 MeV in the FWHM of total kinetic energy distributions is much smaller than the observed difference of almost 3.5 MeV. Thus, where a relatively large effect is predicted theoretically, we observe a small effect, and vice versa.

Thus we may conclude that the liquid-drop model predicts the correct general trends, but does not predict the correct absolute values for the widths of the fragment mass and total kinetic energy distributions. Such deviations from liquid-drop-model predictions are not unexpected, in view of the strong single-particle and shell effects in fission which are expected to occur even very near to the scission point.[7] The case of ^{233}U(^{4}He,f) is not adequately described by the liquid-drop model, and it appears that the model should be used with caution and only as a qualitative approximation for nuclei lighter than radium.

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[10] The fissility parameter x is defined as the ratio of the Coulomb energy of a spherical sharp-surface nucleus to twice its surface energy. Using the expressions and constants of Myers and Swiatecki [Arkiv Fysik 36, 343 (1967)], the fissility parameter is given by

$$x = \frac{Z^2}{50.88A}\left[1 - 1.7826\left(\frac{N-Z}{A}\right)^2\right]^{-1},$$

where Z, N, and A are the proton, neutron, and nucleon numbers of the nucleus, respectively.