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Asymmetric fission

Peter Fong

Physics Department, Emory University, Atlanta, Georgia 30322

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The potential energy surface recently calculated by Mustafa, Mosel, and Schmitt is used for the calculation of the mass distribution curve of fission products of ^{235}U in thermal neutron fission based on the statistical theory. The results obtained agree well with the experimental curve. The physical significance of the agreement is discussed.

[NUCLEAR REACTION, FISSION ^{235}U(n, f), calculated mass distribution.]

Asymmetric fission is a major problem in nuclear physics which has been discussed for three decades.[1] A significant recent advance is the calculation by Mustafa, Mosel, and Schmitt[2] of the potential energy surface as a function of the deformation parameters for the fissioning system after the saddle point nearly all the way to the scission configuration based on the liquid drop model with proper shell corrections calculated according to the Strutinsky prescription. The results for ^{236}U indicate that asymmetric fission modes centered around the mass ratio 140/96 are favored energetically. Experimentally these are indeed the most probable modes in low-energy fission. The qualitative correlation provides a good starting point for a quantitative calculation of the asymmetric mass distribution of fission products. Their results make it possible to carry out a more reliable statistical theory calculation of the mass distribution in thermal-neutron induced fission of ^{235}U.

The statistical theory calculation of mass distribution has been carried out before.[3] The mass distribution function is determined by the total internal excitation energy E of the two fragments at the scission point. According to the statistical theory the energy released, when the fissioning system descends down the potential energy surface, is nearly entirely converted into internal excitation energy (heat energy rather than kinetic energy). The potential energy surface calculated in Ref. 2 enables us to calculate the excitation energy E as a function of the mass ratio of fission. The sophisticated shell correction incorporated in the calculation of Ref. 2 makes it possible to obtain the E function more reliably than ever before.

The E function is calculated by subtracting the potential energy value at the scission point (taken at the neck radius $D = 1$ fm in Ref. 2; see Ref. 4) from the initial excitation energy of the fissioning nucleus ^{236}U taken to be 6.8 MeV (the neutron binding energy) above the ground state in thermal neutron fission of ^{235}U. Then the mass distribution is calculated from the E function in exactly the same way as in the previous work.[3] The distribution is nearly an exponential function of $\sqrt{E}$. As a result, the variation of the probability becomes very large even though the variation of E is rather small. The results obtained are compared with the experimental curve in Fig. 1. It is seen that the main features of asymmetric fission (that the most probable fission modes center around the mass ratio 140/96 and that the ratio of asymmetric to symmetric fission yields is very high, of the order of 10^3) are well reproduced by the statistical theory. Detailed agreement is not expected because of the uncertainties of the model used in potential energy calculation.

The previous statistical theory calculations of mass distribution are based on E functions calculated by less sophisticated methods. From the early works[5] to the latest[6] the statistical theory was able to predict the important fact that asymmetric fissions are favored over symmetric fission by a yield ratio of the order of 10^3. The only drawback is that the most probable mass ratio in ^{236}U is around 132/104 rather than around 140/96. The difference between the ratios 1.3 and 1.4 should be considered relatively minor and is likely to be due to the omission of some yet undiscovered factor in the details of the calculation. However, this discrepancy was often considered a major objection of a fundamental nature against the statistical theory despite the existence of other evidence supporting the statistical theory (charge distribution,[7] kinetic energy and prompt neutron distributions,[8] ternary fission rate,[9] and α-particle angular distribution[10]). In the present calculation the most probable mass ratio falls in the right place and therefore a major objection to the statistical theory is removed. Now let us see what was missing in the previous calculations of the mass distribution.

Comparing the calculations of the E function

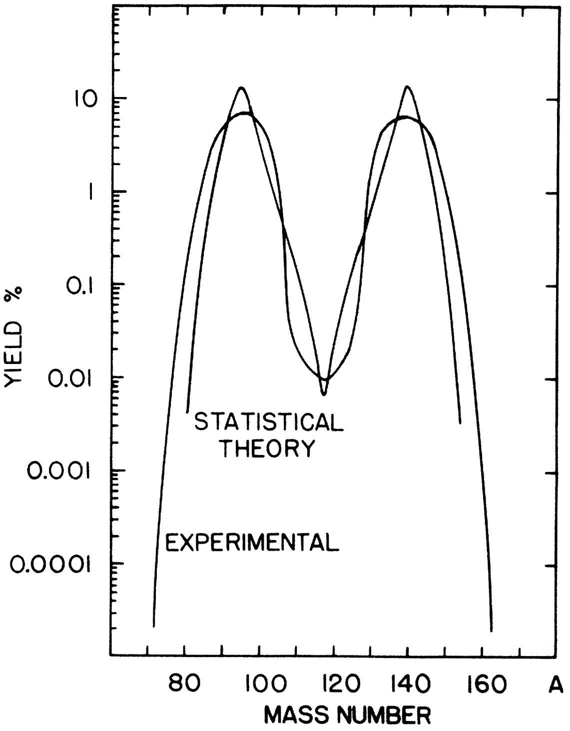

FIG. 1. Mass distribution curve of thermal neutron fission of ^{235}U calculated according to the statistical theory compared with the experimental curve.

based on Ref. 2 and those of earlier works we find that all essential factors of the present calculation were present in the earlier works (and thus the results are expected to be similar to each other) except one important factor—the effect of nuclear deformation on shell structure. As a nucleus deforms the single particle levels shift in position; closed shells may break and new shells may be formed (magic numbers may change from 50, 82, and 126 to other numbers). The fissioning nucleus and the fission products are highly deformed. In the previous works the shell effect on energy is calculated by treating the deformed fission fragments as if undeformed. Thus magic numbers are 50, 82, and 126 and the most probable mode of mass division falls on the ratio 132/104 corresponding to the doubly magic nuclide $^{132}_{50}\mathrm{Sn}_{82}$. This is not the best treatment but previously we did not know how to treat the shell effect under deformation. The Strutinsky prescription used in Ref. 2 is designed precisely to deal with this situation. The inclusion of this effect in the calculation of Ref. 2 corrects a significant deficiency of the previous calculations and with this correction the predicted mass distribution curve indeed agrees well with the experimental results.

A variety of related problems will be dealt with in forthcoming papers.

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[1] See, for example, P. Fong, *Statistical Theory of Nuclear Fission* (Gordon and Breach, New York, 1969).

[2] M. G. Mustafa, U. Mosel, and H. W. Schmitt, Phys. Rev. Lett. 28, 1536 (1972); Phys. Rev. C 7, 1519 (1973).

[3] P. Fong, Phys. Rev. 102, 434 (1956); and subsequent works.

[4] Because this is as far as the calculation has extended and also because a neck radius less than the nucleonic radius has no physical significance.

[5] P. Fong, Bull. Am. Phys. Soc. 1, 303 (1956); R. L. W. Chen and P. Fong, *ibid.* 2, 197 (1957).

[6] A. V. Ignatyuk, Yad. Fiz. 9, 357 (1969) [transl.: Sov. J. Nucl. Phys. 9, 208 (1969)].

[7] J. Wing and P. Fong, Phys. Rev. 157, 1038 (1967).

[8] P. Fong, Phys. Rev. Lett. 11, 375 (1963).

[9] P. Fong, Phys. Rev. C 3, 2025 (1971).

[10] P. Fong, Phys. Rev. C 2, 735 (1970).