Mass Asymmetry in Fission

One of the earliest features observed in the study of fission was the enormous preference for the nucleus to break up into two fragments of unequal mass. This enhancement of asymmetric mass splits relative to symmetric mass splits has since been found to be characteristic for low energy fission of all fissioning nuclei with mass numbers between 230 and 254. Since the discovery of mass asymmetry many other properties of fission have been investigated, including spontaneous fission lifetimes, barrier heights, kinetic energy release, neutron yields, charge distribution and angular distributions of the fragments. Many of the characteristics of these properties have received qualitative, or in some cases even quantitative, explanations which are generally accepted. Innumerable models to account for the observed mass distributions have been proposed over the years but few have survived the scrutiny of time and further experiment. It seems fair to say then that one of the first observations in fission has proven to be one of the most difficult to understand. Recently, however, the calculational methods used to reproduce so successfully the double-humped barriers responsible for fission isomers and intermediate structure have been extended so as to shed considerable light on the origin of the asymmetric mass distributions.

The macroscopic–microscopic method for calculating potential energy surfaces was proposed by Strutinsky.[1] It has been pointed out in a recent Comment[2] that the method as yet does not have a firm theoretical justification. The method has, however, provided results quite similar to those obtained by Hartree–Fock calculations for lighter nuclei where such calculational comparisons are feasible. It has also had considerable empirical success in accounting for barrier heights and isomer excitation energies. Briefly, the method consists of obtaining a shell correction at a given deformation by summing the single particle energy levels appropriate to that deformation and subtracting from this sum a sum over a "smoothed" set of single particle levels. The latter set is obtained by smearing the single particle levels over an energy region somewhat larger than a major oscillator shell. This shell correction, together with a smaller pairing correction, is then added to the charged liquid drop model potential energy surface to obtain a shell-corrected potential energy surface. Thus the microscopic model is not required to reproduce the overall average behavior of the total energy with deformation. The relatively small variations of the total energy with deformation result from strong cancellations between the surface and Coulomb contributions and are difficult to calculate in a self-consistent manner from a fully microscopic method.

To obtain an adequate potential energy surface for all deformations of relevance for fission it is necessary to extend the usual one-center Nilsson potential to potentials which can give a significantly lower nuclear density in the neck region. It is also necessary to consider reflection-asymmetric shapes.[3] Techniques for parameterizing such potentials and for finding their single particle eigenvalues have been developed in the last year or so. The results of calculations performed by different groups[4-7] agree in their essential features. A schematic version of a potential energy surface for ^{236}U is shown in Fig. 1. The shape degrees of freedom exhibited are a necking-in degree of freedom and a mass-asymmetry degree of freedom. The definition of the mass asymmetry is of course difficult for spheroidal shapes which do not exhibit any necking-in.

The equilibrium ground state, the shape isomeric state, and the first saddle separating them, are stable with respect to distortions which are reflection-asymmetric with respect to a plane perpendicular to the longer axis of the nucleus. The saddle for the outer barrier, however, occurs for a quite asymmetric shape. From this saddle a valley runs out and deepens as the shell structure of the nascent fragments develops more fully. (Two equivalent valleys are seen in Fig. 1 because of the inclusion of the mirror image mass divisions in the representation chosen.) As the neck diameter decreases the bottom of the valley corresponds to slightly smaller mass asymmetries than that of the saddle, and for very small neck diameters the minimum occurs at a mass asymmetry very close to that experimentally observed.

What features of nuclear structure are responsible for the second saddle occurring at quite asymmetric distortions? The asymmetry arises entirely from the shell correction, as the liquid drop model potential energy surface for heavy nuclei always has a minimum for symmetric shapes. To a certain extent the favoring of asymmetric distortions by the shell structure is a consequence of a very unfavorable shell correction at the outer barrier for symmetric distortions. Evidence has been presented[8,9] which indicates that the degeneracies associated with the final fragment shell structure are already felt for distortions considerably less than that of the final scission configuration. This is apparent in Fig. 1, where the deep valley at scission is seen to extend back to the second saddle. The role of certain single particle orbits in producing an instability of the outer barrier with respect to asymmetric distortions has been emphasized.[10] The presence of these orbitals near the Fermi surface for

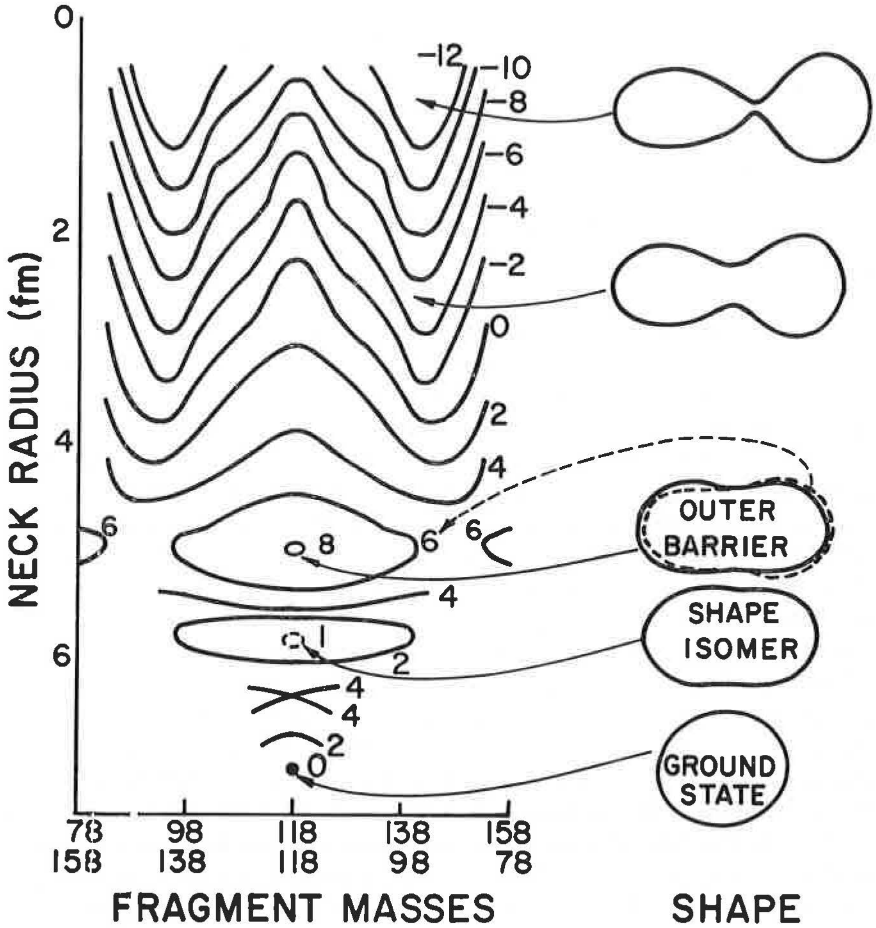

FIG. 1. Potential energy surface for ^{236}U. Contour intervals are 2 MeV, except for that of the shape isomer. Adapted from results presented in Ref. 7.

deformations near the second saddle has been attributed[11] to the developing level structure of the final fragments.

It has been suggested that the mass division may be determined already by the time the nucleus leaves the second saddle and that one need not consider further the potential energy surface at larger deformations. This view is inconsistent, however, with the situation obtaining for lighter elements, such as lead and polonium, which experimentally are observed to exhibit symmetric-mass yield distributions. Most of the calculated potential energy surfaces, however, exhibit a barrier with the saddle occurring at a very asymmetric distortion. From this saddle a flat plateau leads to a single well-developed valley corresponding to symmetric distortions.

It is also interesting to consider what happens for nuclei much heavier than uranium. There are calculations which suggest that the heaviest fermium isotopes ($Z=100$) would be expected to fission symmetrically. Indeed there are experimental results indicating an increasing tendency towards symmetric fission with increasing neutron number for the fermium isotopes. Unfortunately possible excitation energy effects need to be sorted out before a conclusive verification can be claimed.

In the previous discussion we have implied that the expected mass distributions could be inferred by examining the valleys in the potential energy surface. One must remember, however, that the appearance of potential energy surfaces depends on the coordinate representation chosen. The intuitive expectation of sliding down the bottom of the valley in Fig. 1 is certain to be realized if the inertial parameter is independent of the direction of the velocity vector for any accessible point on the potential energy surface. Less stringent restraints on the inertial parameter may lead to the same result. This leads us to a final plea to the theorists. Do not abandon the problem when it is only half-solved! Although the potential energy surface is probably adequately understood for our present purposes, the dynamics are almost completely unexplored. It is realized that a calculation of the dynamics poses difficult problems, both theoretical (is the cranking model adequate for calculating inertial masses for large distortions?) and practical (consider the large number of possible trajectories in a multidimensional space). Nevertheless the dynamics associated with nuclear distortions reach their full extremes in the process of nuclear fission, and there may be some new lessons to be learned. In the descent from saddle to scission the potential energy surface decreases by several tens of MeV. It is still uncertain to what extent the distortion is adiabatic. This will depend on the viscosity of nuclear matter. These questions are of considerable interest at the present time, as new heavy ion accelerators make possible the study of the amalgamation of two very heavy nuclei.

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