SYMMETRY OF NUCLEAR FISSION

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It is noted that an asymmetric mass distribution of fission fragments is observed only in nuclei with an appreciable number of nucleons outside the closed shells with Z = 82 and N = 126. It is suggested that the external nucleons are responsible for the instability of the fissioning nucleus with respect to asymmetric deformations. The consequences of this assumption are shown to be in agreement with available experimental data.

SHORTLY after the discovery of fission it was established that the mass-number distribution of the fragments is not symmetrical. This asymmetry appeared to be a general property of the fission process in heavy nuclei at not too large excitation energies (up to 30 or 40 MeV), and it has been a topic of consideration in many articles. In a series of articles it was shown that shell effects in the fission fragments are responsible for the asymmetry. However, experimental data of recent years show that not all nuclei give asymmetric distributions; the nature of the fission symmetry (whether the fission will be symmetric or asymmetric) is strongly dependent on what kind of nucleus undergoes fission. These data compel us to question the decisive role supposedly played by shell effects in the fragments (the composition and excitation energy of which does not change very much from nucleus to nucleus) in determining the symmetry nature, and we are impelled to look for a reason in the structure of the fissioning nuclear species itself.

The experimental data referred to pertain principally to fission of elements lighter than thorium, induced by medium-energy particles. It was shown [1,2] that, in contrast to elements heavier than thorium where fission is predominantly asymmetric, lead and bismuth (upon irradiation by 22 MeV deuterons or α particles of energies up to 43 MeV) give a rather narrow symmetric mass-number distributions of fragments. On the other hand, the mass distribution of fragments from fission induced in radium (the atomic number of which occupies an intermediate position between lead and thorium) by 11 MeV protons and 22 MeV deuterons appears to have both symmetric and asymmetric parts. Similar results were also obtained when fission was induced by γ rays. [3]

We now turn our attention to the structure of the nuclei under consideration. The nuclei $_{82}Pb^{207,206,204}$ and $_{83}Bi^{209}$ are very close to the doubly-magic nucleus $_{82}Pb^{208}$. They have a very small excess (or deficiency) of nucleons with respect to closed shells and are spherically symmetric. Nuclei of heavier elements have a larger number of nucleons outside of closed shells. These external nucleons, acting on the nuclear surface, produce dynamical deviations from spherical symmetry. Upon further increase of the atomic weight of the element, the number of nucleons outside the closed shells also increases, and their effect becomes so strong that they produce a static deformation of the nucleus. At some stage a "shape saturation" effect sets in—a further increase in the number of nucleons does not produce any additional deformation. Thorium and all heavier nuclei belong to this class. They all have approximately the same deformation ($\beta^2 = 0.12$). The magnitude of the deformation is smaller for radium ($\beta^2 = 0.08$). Apparently the number of external nucleons in this nucleus is still not large enough, and it occupies an intermediate position between dynamically and statically deformed nuclei.

Thus, one can remark that when the number and, consequently, also the effect of the external nucleons is large (thorium and heavier nuclei) fission is asymmetrical; in the opposite case (lead and bismuth) the fission is symmetrical; in intermediate cases both symmetric and asymmetric fission modes are observed. It appears that the external nucleons also determine the symmetry nature of the fission process. In this connection, it is probable that they only generate an asymmetry that causes an instability of the shape of the fissioning nucleus with respect to asymmetric deformations. The magnitude of the asymmetry (the magnitude of the most probable mass ratio of the fragments) is apparently, as suggested previously, determined by shell effects in the fragments.

Since the external nucleons abruptly change the states of the nuclei in the region between lead and thorium, the reason for the dramatic change in the symmetry nature of the fission process becomes clear. In particular, one can understand the results of recent experiments on radium fission induced by deuterons and α particles.[5]

If the external nucleons cause the asymmetry, then one can think that the fission process in elements slightly lighter than lead (i.e., elements in which the closed shells are not completely filled) should be similar, with regard to the mass distribution of fragments, to that in elements slightly heavier than lead. In this connection, it is of interest to note that the cited article by Jensen and Fairhall [5] reports a broadening of the mass distribution curve on going from Pb^{206} to Pb^{204} and then to Au^{197} (i.e., as the fissioning nucleus becomes farther removed from the doubly magic number). This effect may indicate the appearance of asymmetric fission similar to the fission of heavier elements.

The rapid increase in the fraction of symmetric fissions, occurring with increased excitation of the fissioning nucleus, may be attributed to breakdown of shell structure and the fact that the nucleus comes closer to the liquid-drop model. One can expect a more rapid increase of the shape of symmetric fission in nuclei with few nucleons outside the closed shells (e.g., radium); this effect has indeed been observed experimentally.[6] Further experimental verification is needed for the ideas presented here concerning the symmetry of nuclear fission.

[1] A. W. Fairhall, Phys. Rev. **102**, 1335 (1956).

[2] Fairhall, Jensen, and Neuzil, Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Vol. 15, p. 452, Paper 677.

[3] Duffield, Schmitt, and Sharp, Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Vol. 15, p. 202, Paper 678.

[4] A. Bohr, Rotational States of Atomic Nuclei (Ejnar Munksgaards Forlag, Copenhagen, 1954).

[5] R. C. Jensen and A. W. Fairhall, Phys. Rev. **118**, 771 (1960).

[6] R. A. Nobles and R. B. Leachman, Nuclear Phys. **5**, 211 (1958).

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28