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Study of fission fragment mass distributions

Fission is an important decay mode and physics of this process is crucial in determining stability of heavy and super-heavy isotopes. Although the fission process itself has been known for almost eighty years, a full, theoretical description of its mechanism is still a research challenge. The atomic nucleus is a complicated system of short-range nuclear forces of quantum objects (nucleons). The tools of quantum mechanics, used to describe the phenomena and objects of the microworld, require knowledge of the forces of interaction, which in the case of nucleons have not been fully understood.

One of the basic, measurable fission characteristics is the fission fragment mass distribution. These data are useful for further analyzes in the purely theoretical context - description of nucleosynthesis in the r-process - and applications: improvement of engineering solutions, such as work on optimization of fuel cycles in the nuclear industry energy, handling of radioactive waste, etc. Thus there is a need to develop a predictive theory that could explain mechanisms which are experimentally inaccessible. So far the mechanism of mass dividing between fragments during fission has not been theoretically described in a way that allows to reproduce experimental data with sufficient accuracy.

The aim of this work was to study the collective mechanisms that are crucial in the process of splitting nucleons between fragments of fission. The main task was to answer the following questions: how important are macroscopic factors in description of nuclear fragmentation; how dynamic effects determine the shapes of mass distributions and which degrees of freedom of nucleus' deformation are important for the description of the fission process in the context of mass distribution between products. There were studied isotopes, representing two observed in nature types of fission: ^{252} Cf, ^{256} Fm, ^{180} Hg (asymmetric mass distribution) and ^{258} Fm (bimodal). The basic research tool used in this work is the Hartree-Fock-Bogoliubow (HFB) model, which treats the atomic nucleus in a microscopic manner, discussed in more detail in subsection 2.1. Subsection 1.2. is an introduction to the undertaken research issues. It contains a short history of discovery of nuclear fission and motivation for this reasearch. At the end, important models were briefly discussed and used to predict the distribution of the mass of fission fragments.

Chapter 2 covers the results of carried out analyzes of pre-scission points - the last configuration of the connected nucleus, lying at the end of the preferred fission path, determined by the method of energy minimization. The spatial density distributions of nucleons corresponding to these shapes allowed to draw conclusions about the structures of the derived nuclei formed at this stage, and thus to pre-determine the mass of the most probable fragments. It has also been shown that - on the basis of these profiles, one can initially conclude on the shape of the distribution of fission mass by linking the probability of observing a given mass division with the probability of tearing the neck of the nuclide at the site corresponding to such fragmentation. The obtained mass distributions were compared with the experimental ones.

Chapter 3 is devoted to the dynamic description of the fission process. The evolution of the wave packet, corresponding to the initial state of the splitting nucleus, was carried out in a two-dimensional configuration space. The isotope ^{252} Cf was examined in detail. The influence of initial conditions on the received mass distribution of fragments is discussed. The results obtained for the nuclides ^{252} Cf, ^{256} Fm, ^{258} Fm were presented and compared with the experiment.

Based on the obtained results, it can be concluded that - at least in part - it was possible to understand the essence of collective mechanisms responsible for the division of nucleons between fission fragments. The results of static studies have shown that even the mere analysis of the configuration preceding the rupture provides essential information about the physics of the fission process. Considering the distribution of spatial nucleon densities in this advanced phase of deformation, there can be drawn conclusions regarding the internal structure, shape, and mass of the most probable products, and thus predefined the type of fission (symmetrical or asymmetric). The mass distributions of fragments calculated using the macroscopic B method of Brosa reproduce with fairly good accuracy the mass of the most probable fragments - heavy and light - observed in the experiment. Thus, it has been shown that the hydrodynamic macroscopic effects associated with the surface energy of the splitting isotope are also significant in the nucleon division process. The obtained insufficient width of theoretical distributions is the result of the omission of shell and dynamic effects.

The results of dynamic calculations have shown that the shape of the distribution weakly depends on the parity of the wave packet, its excitation energy or - for states that are a linear combination of eigenvalues - the selection of a statistical method of their mixing. However, research on the isotope ^{256} Fm showed that - in the case of positive parity states lying above the fission barrier, with the increase of the level energy, in the obtained mass distribution the probability of observing symmetrical fragmentation increases, which is consistent with the experiment. Finally, it should be noted that mass distributions obtained in a dynamic approach combined with the method of Brosa are in a better agreement with experimental data in comparison to the distribution resulting from only macroscopic analyzes. Thus, it has been proved that dynamic effects are an indispensable aspect for understanding the mechanism of mass division in the fission process.

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