SYSTEMATIC ANALYSIS OF STRUCTURAL EFFECTS IN FISSION-PRODUCT YIELDS AND NEUTRON DATA AND THE CONSEQUENCES FOR OUR UNDERSTANDING OF THE FISSION PROCESS AND THE PREDICTIVE POWER OF MODEL PREDICTIONS

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Structural effects in fission-product yields and neutron data for a large number of fissioning nuclei between ^{220}Th and ^{256}Fm from spontaneous fission to 14-MeV-neutron-induced fission have been used to deduce information on the properties of the fissioning systems. Macroscopic properties are attributed to the compound nucleus, while fission channels are ascribed to shells in the nascent fragments. Using a recent general empirical description of the nuclear level density and assuming different characteristic time scales for the collective degrees of freedom of the fissioning system, a new fission model has been developed. The model combines the statistical concept of the scission-point model of Wilkins et al. with empirically determined properties of the potential-energy surface and some characteristic dynamical freeze-out times. Although no fine tuning of the parameters has yet been performed, the model reproduces all measured fission yields and neutron data rather well with a unique set and a relatively small number of free parameters. Since the parameters of the model are closely related to physical properties of the systems, some interesting conclusions on the fission process can be deduced. Prospects for the predictive power of this semi-empirical approach for hitherto unknown fissioning systems are discussed.

Keywords: Fission-fragment yields; fission channels; fission dynamics; macroscopic-microscopic approach; separability principle; energy sorting; even-odd effect.

1. Introduction

Ordering schemes, systematics and semi-empirical models are powerful approaches for advancing our understanding of complex phenomena in nature. In nuclear fission great progress has been made by introducing the general concept of fission channels.[1] It established a link between the observed characteristics, e.g. in fission yields and kinetic energies, and the properties of the potential-energy surface of the fissioning system. However, it did not allow for quantitative predictions. The theoretical description of nuclear fission, in particular at low excitation energies with its rich manifestation of nuclear-structure phenomena is still a challenge. At present, one is restricted to purely empirical models (e.g.[2]) for a good quantitative description of the data.

In contrast, the theoretical description of atomic masses has reached a high degree of precision, and the complex phenomena behind the manifold global and structural effects are quantitatively rather well understood. The data are very well reproduced by models based on the macroscopic-microscopic approach, while fully microscopic models are supposed to be more realistic for nuclei close to the drip lines.

In the present contribution we try to profit from the successful concepts and methods used in mass models in order to establish an improved model of the fission process. We make use of several well-known and a few newly developed concepts to develop a description for fission-fragment distributions and the properties of prompt neutrons, which reproduces the experimental data with high precision and which is expected to have a high predictive power for systems that have not been measured and that are not accessible to experiment.

2. Reminder on methods and concepts used in mass models

Atomic mass models[3] span the range from local formulas,[4] directly based on measured mass values, to microscopic models based on effective nucleon-nucleon interactions. However, intermediate approaches proved to be the most successful ones for a long period. A rather good description of the binding energy of atomic nuclei has been proposed by C. F. von Weizsaecker already in 1935. It relies on the analogy of an atomic nucleus with an electrically charged drop of a classical liquid. By additionally considering the Fermionic nature of the nucleons by the asymmetry term, the liquid-drop model reproduces the nuclear binding energies with a precision of about 1 per cent. In the macroscopic-microscopic approach, structural effects due to shell effects and pairing correlations are calculated separately by the Strutinsky method[5] and added to the value obtained by the liquid-drop model. The liquid-drop model still gives a very good estimation of the global behaviour of nuclear binding for nuclei not too close to the drip lines, which is at present hardly reached by microscopic models that rely on the interactions of nucleons governed by an effective nuclear force.

A systematic analysis of empirical data and a careful comparison with global models, like the liquid-drop model, have proven to be very useful in establishing evidence for phenomena, which go beyond the basic description. Exceptionally high binding of nuclei along ”magic numbers” due to shell effects,[6,7] even-odd structure due to pairing correlations and the manifestation of the congruence energy[8] were recognized by systematic deviations from the liquid-drop predictions. The role and the magnitude of the spin-orbit force have been deduced,[9,10] and the appearance of new magic numbers far from stability has been evidenced.[11] The comparison of nuclear properties with a global background acts as a magnifying glass on structural effects and new phenomena and, thus, forms the important counterpart to microscopic models, which try to model the complex phenomena on a more fundamental level. One should not forget that also microscopic nuclear models remain phenomenological,[12] since the effective force is adjusted to reproduce best the body of experimental data.

3. Concept of a general fission model

The experimental information available in low-energy fission of a specific nucleus is by far more rich than just one numerical value like its atomic mass: These are the many individual nuclide yields, the kinetic energies of the fission fragments, the prompt neutron yields and neutron energies, to mention the most prominent ones, only. Moreover, the fission observables are the result of a complex dynamical process, while the ground state of a nucleus is the energy of an equilibrium state. Thus, the modeling of the fission process appears to be much more difficult.

Any fission model needs to follow the dynamic evolution of the fissioning system up to scission. The number of protons and neutrons in the two fragments, their kinetic energies, the available energies above their respective ground states as well as their angular momenta are decided or can uniquely be deduced from the scission configuration. However, it is not justified to assume statistical equilibrium at scission as it was done by Wilkins et al.,[13] because a considerable inertia may prevent the system to adjust instantaneously to the bottom of the potential-energy valley on the fission path. One may assume that there is a dynamical freeze-out somewhere before reaching scission, which is specific to the different collective variables. The mass asymmetry degree of freedom is characterized by a rather early freeze-out due to its large inertia, while the N/Z degree of freedom is decided later, because the mass transport and consequently the inertia associated with the charge polarization is much lower. Thus, there is no single, well defined configuration, where a statistical-model assumption seems to be justified.

Due to this difficulty and the unavoidable uncertainty of a theoretical fully dynamic calculation, we decided to extract the relevant information from the available experimental data directly. The measured characteristics of the distributions in the different variables contain the required information in the most precise and realistic way. However, it is not clear, whether this approach is feasable, because we should establish this empirical information for each fissioning system independently. Thus, this approach would be equivalent to a purely empirical model with a specific parameter set for each fissioning system. One cannot expect a high predictive power for unmeasured systems from this kind of approach.

The application of the separability principle[14] solves this problem. Indeed, two-centre shell-model calculations revealed that the shell effects of the fissioning system already immediately beyond the outer saddle are very similar to the sum of the shells in the two nascent fragments.[15] The combination of this finding with the macroscopic-microscopic approach leads to a very important conclusion: The shell effects on the fission path are associated to the nascent fragments. Essentially the same shell effects are present if the same fragments are formed in different fissioning systems. Thus, the full body of experimental data on fission-fragment properties can be used to deduce the relevant information on shell effects on the fission path, which are the same for all fissioning systems. Only the macroscopic potential on the fission path is specific to the fissioning system. The separability principle of microscopic effects, which are associated to the nascent fragments, and of macroscopic effects, which are specific to the fissioning system, make our approach feasable and gives it a high predictive power.

4. Formulation of the model

A basic ingredient of the model is the curvature of the macroscopic potential in mass-asymmetry on the fission path at freeze out of the asymmetry degree of freedom.[16] This value determines the width of the mass-symmetric fission channel and, even more importantly, the relative strengths of the asymmetric fission channels. The shell effects, which are responsible for the asymmetric fission valley are fully effective, if they appear close to symmetry. This is the case for the heavier actinies. In contrast, the influence of these shell effects is weakened in the lighter actinindes, where these shells appear at larger asymmetry. This interplay of the macroscopic potential and the shell effects determines the transition from single-humped mass distributions to double-humped distributions around $A = 226$.

We present here in some detail the analysis of the mean position of the

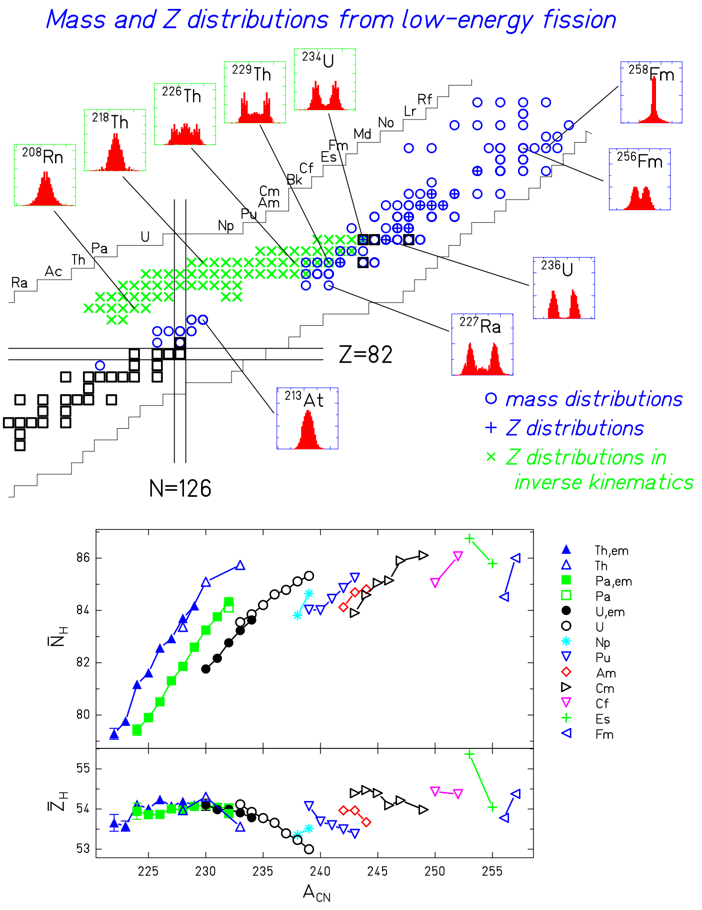

Fig. 1. Upper part: Overview on the systems, for which mass or nuclear-charge distributions have been measured. The green crosses denote the systems which have been measured in inverse kinematics after electromagnetic excitation.[17] Lower part: The mean position of the asymmetric component in the heavy group in neutron number and in atomic number. Obviously, the traditional statement that the heavy component is constant at $A = 140$ must be revised by this analysis on a finer scale: The position of the asymmetric component is nearly constant at $Z = 54$, while the position in neutron or mass number varies by about 7 units.

heavy component of the fission-fragment distribution as an example of the many ingredients of the fission model. Fig. 1 shows the systems, for which mass or nuclear-charge distributions have been measured, on a chart of the nuclides. The position of the heavy component shows a regular pattern, but the previous assumption[18,19] that the position is constant in mass appears to be strongly violated. It is rather the proton number, which is fixed at $Z = 54$. For this finding, the long isotopic chains studied in an experiment in inverse kinematics play a decisive role.[17] Thus, we implement in our model that the freeze out of the mass-asymmetry degree of freedom leads to a nearly constant position in the atomic number of the heavy fragment. A similar kind of analysis has been made for the different fission channels, which are considered in the model.[20]

Some other structural effects, which were deduced from experimental data, are the Z-dependent deformation parameters of the fragments and the mean value and the width of the charge polarisation at scission. The fractions of the energy release from saddle to scission which end up in intrinsic and collective excitations have been fixed, too. Another important ingredient of the model is the energy-sorting mechanism,[21] which is responsible for the division of the intrinsic excitation energy at scission and for the creation of an even-odd effect in asymmetric mass splits.[22]

Finally, the model includes an evaporation code, which determines the prompt neutron yields from the two fragments as well as their kinetic energies. Gamma competition is considered; it smoothes out the consequences of the even-odd fluctuations of the neutron-separation energies.

More detailed information on the code, which we called GEF (GEneral Fission model), including a comprehensive comparison with experimental data can be found here.[23] The GEF code can also be downloaded, which allows performing dedicated calculations.

5. Conclusions

A new fission model has been developed. It is based on the statistical population of states in the fission valleys at the moment of dynamical freeze-out, which is specific to each collective degree of freedom. Three fission channels are considered. The separability principle governs the interplay of macroscopic and microscopic effects. The newly discovered energy-sorting mechanism determines the division of intrinsic excitation energy between the fragments at scission and the creation of a strong even-odd effect at large mass asymmetry. This new model gives a new insight into several dynamical times.

The GEF code provides a consistent description of the fission observables from polonium to fermium, from spontaneous fission to initial excitation energies up to about 14 MeV, with the same parameter set. (For higher excitation energies, multichance-fission must be considered.) Most parameters are fixed from independent sources, only less than 20 parameters have specifically been adjusted. Since the parameters of the model are closely related to physical properties of the systems, valuable conclusions on the fission process can be deduced. The good reproduction of measured data and the high predictive power of the code make it useful for applications in nuclear technology and complement the use of purely empirical models.

Acknowledgments

This work was supported by the EURATOM 6. Framework Programme "European Facilities for Nuclear Data Measurements" (EFNUDAT), contract number FP6-036434.

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