THE BUSINARO–GALLONE REGION: A PLAYGROUND FOR DYNAMICAL MODELS OF FISSION?*

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Nuclei in the Businaro–Gallone region are proposed as a relevant tool to study the dynamics of nuclear fission at high temperature. The influence of the macroscopic contribution to the driving potential energy landscape, and its strong dependence on angular momentum, is addressed in this contribution as a first step. An advanced model based on a four-dimensional Langevin approach is used to calculate fission-fragment mass and charge distributions. A good agreement with experiment is observed. The work is in progress, with the goal to explore the major assets of nuclei in this region for probing the modeling of inertia, friction and fluctuations, and particle evaporation.

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1. Motivations

Fission is recognized as a very rich laboratory for learning about various fundamental nuclear properties. As such, it is also particularly challenging to describe, since the interplay between various more or less (poorly) known

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effects leads to an intricate puzzle. That puzzle remains unsolved today. Depending on the aspect targeted by a specific study, the investigation can widely benefit from a smart choice of the system. Fission of nuclei located in the Businaro–Gallone (BG) region [1] (with masses A around 100–130) has been proposed as a relevant tool to study some nuclear properties already 30 years ago [2, 3]. These systems can fission only provided a sufficient amount of excitation energy (E^*) and/or angular momentum (L) is imparted to the initial compound nucleus (CN). Influence from microscopic structural effects can be neglected, and macroscopic aspects of nuclear matter can be studied under "clean" conditions. Conversely, fission of heavier nuclei at low and intermediate excitation energies may be best suited to study the influence of fragments shells effects and their damping. Since these systems are committed to fission anyway, and usually follow pronounced valleys in the potential energy landscape (hereafter PES), they are less sensitive to the dependence of the PES on L, to the detailed modeling of transport coefficients and particle emission, and their dependence on deformation. By contrast, the fate of medium-mass nuclei can be dramatically influenced, on their hesitant way to fission, by subtle variation of these effects. The potential energy topography in the reflection-asymmetry degree of freedom is pretty flat, and strongly dependent on angular momentum. The evolution of the system may thus be particularly sensitive to the influence of inertia, dissipation, and associated fluctuations. Also, emission of light particles prior fission may change the story completely. Finally, medium-mass systems are characterized by fairly balanced cross sections in the fission and evaporation-residue channel. That enlarges the number of observables, so that poorly known model parameters can be better constrained [4].

So far, only a qualitative understanding of fission in the BG region could be achieved [2, 3], and studies of such systems region have to been set in stand-by for quite a while. Realistic dynamical calculations were not available, and the limited fissility involved requires computing resources which were not available till recently. Priority was naturally set to heavy systems, which can be measured in number and fast, and a description of which is less sensitive to subtle details. It is the goal of our project to exploit today available theoretical and computing resources for revisiting fission in the BG region.

2. Theoretical framework and strategy

The model used in this work is based on the stochastic classical approach of fission dynamics. Dynamical calculations were performed with the Langevin code developed by Nadtochy and collaborators [5]. Fission is modeled considering four collective coordinates: Three variables describe the shape of the nucleus according to a slightly modified variant of the well-known Funny-Hills parameterization [6], and a fourth coordinate corresponds to the orientation of its angular momentum relative to the symmetry axis. The evolution of these variables is computed time-step-by-time-step from the solution of the multi-dimensional Langevin equations of motion

$$\begin{aligned}\frac{dq_i}{dt} &= \mu_{ij} p_j \,, \\ \frac{dp_i}{dt} &= -\frac{1}{2} p_j p_k \frac{\partial \mu_{jk}}{\partial q_i} - \frac{\partial F}{\partial q_i} - \gamma_{ij} \mu_{jk} p_k + \theta_{ij} \xi_j \left(t\right) \,,\end{aligned}$$

where $\boldsymbol{q}$ and $\boldsymbol{p}$ are the vectors of collective coordinates and momenta, respectively. The driving potential $F(\boldsymbol{q}, K)$ is given by a temperature-dependent Liquid-Drop PES [7]. More specifically, in this work, the potential energy of the nucleus is calculated within the framework of the macroscopic model with a finite range of the nuclear forces [8] using the parameters from Ref. [9]. The potential energy is thus obtained as a sum of the Coulomb energy, the generalized surface energy (nuclear interaction energy), and the rotational energy. The quantities $\mu_{ij}(\boldsymbol{q})$, $\gamma_{ij}(\boldsymbol{q})$ and $\theta_{ij}\xi_j\left(t\right)$ refer to the tensor of inertia, friction, and fluctuations, respectively. The calculation of these transport coefficients is based on common macroscopic concepts (see Ref. [5] for details). The initial conditions corresponds to a compound nucleus assumed to be spherical. The calculation of the trajectory stops when scission, defined as a strongly necked-in configuration of two nearly-distinct fragments [10], is reached. De-excitation of the system by evaporation of light particles prior scission, and by the fragments after scission, is simulated along the time evolution of the fissioning system by employing the Monte Carlo approach. We emphasize that the theoretical framework used in this work does not account for microscopic effects. This is not a limitation in the BG region, since fission is restricted to high temperature (T). The 4D code by Nadtochy *et al.* [5] represents state-of-the-art in the field of fission dynamics at moderate to high T; it has shown impressively powerful in describing a wide set of experiments.

3. Results

We propose to use the above-outlined formalism to address fission in the BG region, and explore its potential for understanding specific aspects of fission dynamics. In the present contribution, we discuss the delicate influence of angular momentum on the PES in governing the fission-fragment mass (charge) distribution. The influence of inertia, friction, particle evaporation, their dependence on deformation, as well as the survey of other fission properties, will be communicated elsewhere.

At zero angular momentum, the PES undergoes a topological change when the fissility parameter ($\approx Z^2/A$) crosses the Businaro–Gallone point [1]: below that point, there is no more a traditional symmetric fission saddle point, and very asymmetric "evaporation-like" partitions are favored. The location in fissilitly of the BG point depends critically on L [2]. The emergence of an effective — L-dependent — fissility makes nuclei in the BG region presenting "odd" fission properties. Indeed, a given nucleus can be located either below or above the BG point, depending on its L. In other words, in case it is committed to fission, the shape of the fragment distribution can be totally different depending on the entrance-channel reaction (*i.e.* on L). This characteristic feature of the BG region is illustrated in Fig. 1. For the lightest systems (^{102}Rh, ^{110}Sn), the fission barrier exhibits a dramatic dependence on L, while for heavier nuclei, symmetric fission is favored by the PES for all Ls. In addition, since the PES is pretty flat in the asymmetric direction for BG systems, the trajectory may be influenced as well by *a priori* second-order effects, like the magnitude and dependence on deformation of inertia, friction, fluctuations, and particle evaporation. In this sense, the BG region is hoped to be a pertinent choice for probing such effects.

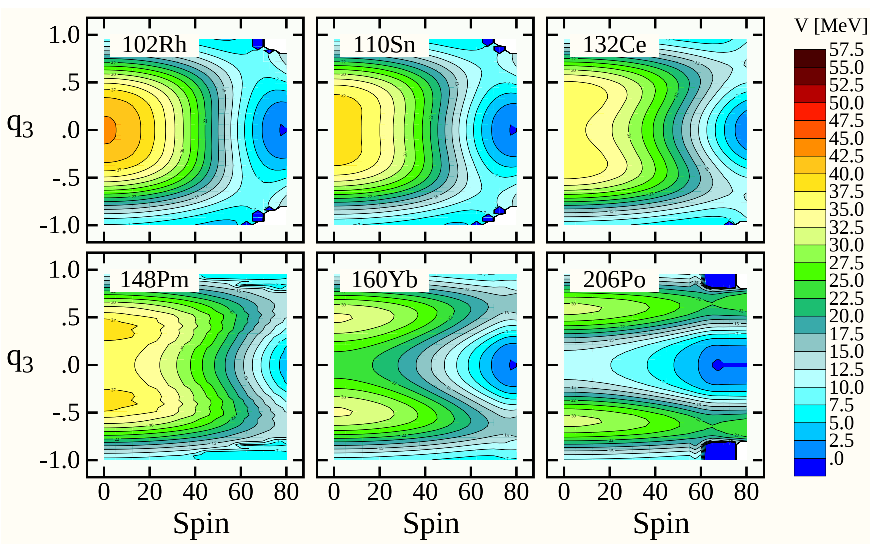

Fig. 1. (Color on-line) Surface plot of the asymmetry- (here q_3) and L- (here spin) dependent fission barrier for a few nuclei as predicted with the Finite Range Liquid Drop Model implemented in Ref. [5].

The BG transition has been investigated experimentally in few instances [3, 11–13] only, due to the substantial beam time required to measure properly the fragment distribution of such low-fissility systems. As noted previously, theoretical interpretation remained at the qualitative level so far, and this work represents the first attempt to throughly investigate — with an advanced dynamical model, a series of systems straddling the BG point. The shape of the fragment distribution depends on fissility and angular momentum (see Fig. 1). In addition, it depends on temperature, since the driving potential is the Helmholtz free energy [5]. Nonetheless, the influence of intrinsic excitation is anticipated to be weaker than that of L in this particular BG case: It mainly affects the widths of the distributions, and not the basic shape.

Available judicious cross-bombardments are used to form the same CN at similar T, but different L, or a different CN at similar T and L, *etc.* A first step in this direction is made in Fig. 2. The left panel clearly illustrates the influence of fissility, by comparing the fragment Z distribution for different CN produced at similar T and L. The right panel shows the influence of L for a specific CN. Note that, in each case, the calculation is performed for an L distribution which is in agreement with experimental estimate. The correct trend achieved here for the first time quantitatively, within a realistic dynamical model, is rather remarkable.

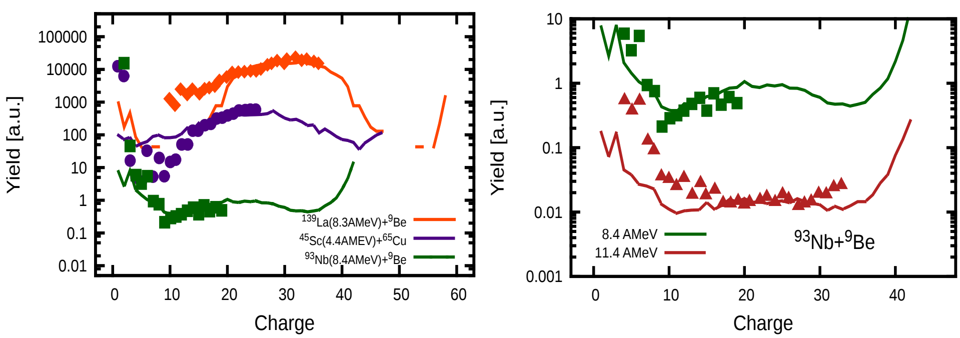

Fig. 2. (Color on-line) Fission-fragment charge Z distribution for different reactions: (left panel) ^{93}Nb (8.4A MeV) + ^{9}Be → ^{102}Ru, ^{45}Sc (4.4A MeV) + ^{65}Cu → ^{110}Sn, ^{139}La (8.3A MeV) +^{9}Be → ^{148}Pm, and (right panel) ^{93}Nb + ^{9}Be → ^{102}Ru at 8.4 and 11.4A MeV. The calculations shown by lines are compared to experiment (symbols) [3, 11–13]. Staggering in the theoretical curves is due to statistics. Yields of the different system have been arbitrarily scaled for legibility. The fissility parameter amounts to 0.386, 0.453 and 0.523 for ^{102}Ru,^{110}Sn, and ^{148}Pm, at $L = 0$.

4. Conclusions and outlook

Systems located in the BG region are promoted to selectively study the influence of macroscopic effects on fission. The evolution of the fragment Z distribution with CN fissility and L is attempted and properly described with an advanced 4D dynamical fission model for the first time. A meticulous investigation is in progress to further exploit the potential of the BG transition region in order to probe the modeling of transport coefficients and particle evaporation in current fission models. Understanding this critical transition region is anticipated as giving new, further impetus in dynamical fission investigations, fully complementary to studies on heavier systems.

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