

Microscopic description of ^{258}Fm fission dynamic with pairing

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Abstract

Fission dynamic remains a challenge for nuclear microscopic theories. In order to understand the dynamic of the last stage of the fission process, the time-dependent Hartree-Fock approach with BCS pairing is applied to describe the fission of the ^{258}Fm . A good agreement is found for the one-body observables: the total kinetic energy and the average mass asymmetry. The non-physical dependence of two-body observables with the initial shape is discussed.

1 Introduction

The fission process is an ideal phenomenon to test the predictive power of dynamical theories. Indeed, this process incorporates many aspects of nuclear dynamic, dissipation, superfluidity, tunneling, as well as a large number of degrees of freedom. The fission dynamic has been the object of several approaches: Brownian motion on the potential energy sur-

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face [1], time-dependent generator coordinate method (TDGCM) [2], time-dependent Hartree-Fock (TDHF) [3] and adiabatic models that suppose that the two fragments choose the path that minimizes the energy from the initial well to the scission point.

The adiabatic assumption is often assumed along the fission process, where the friction is important and so the evolution is slow enough to follow the path that minimizes the energy. Nevertheless, close to scission, non-adiabatic effects play an important role [4]. A smooth transition occurs between the adiabatic motion when the two fragments are in contact and the fast evolution due to the Coulomb repulsion when the neck is broken. This transition involves many degrees of freedom: distance between the fragments, deformations of the fragments, neck configuration ... The TDHF theory is an ideal tool to study this process as it makes no restriction on the shape of the one-body density. Then the results do not depend of an arbitrary choice of parametrization of the nuclear shape during the scission.

In order to take into account pairing in the TDHF framework, the natural candidate is the time-dependent Hartree-Fock-Bogoliubov theory (TDHFB). The TDHFB theory is numerically demanding [5]. In consequence, we choose to adopt the TD-BCS approximation. In several studies, it has been shown that the BCS approximation is a good compromise to take into account pairing in the mean-field framework. In particular, comparisons to QRPA calculations show a good agreement with the BCS approximation for the small amplitude motion [6, 7].

2 The fission process

In order to study the fission process, the system is first initialized after the barrier on the adiabatic path. This initialization is done using the Constraint Hartree-Fock with BCS approximation (CHF+BCS). A modified version of the code EV8 [8] has been used, where two of the reflection symmetry have been removed allowing the octupole deformation necessary to study asymmetric fission. As a test case, we study the ^{258}Fm fission where experimental data are available [9]. In the literature, three modes are considered: a symmetric fission with compact fragments, a symmetric fission with elongated fragments and an asymmetric fission. The three modes exhibit different dynamical behaviors due to different structure effects and Coulomb energy at the scission point.

Using the CHF+BCS, the evolution of the potential energy is shown on fig. 1 (right). Each mode is associated with a valley in the 3 dimensional

space (Q_{20} , Q_{30} , Q_{40}) and is shown here as a function of the distance between the two fragments. Similar results for the potential energy as a function of the deformation for the three modes have been found using different interactions or methods in ref. [10, 11]. Starting from the three valleys, three corresponding TD-BCS evolutions have been done. The evolutions until complete scission are shown on the fig. 1 (right) . The details of the calculation can be found in ref. [12].

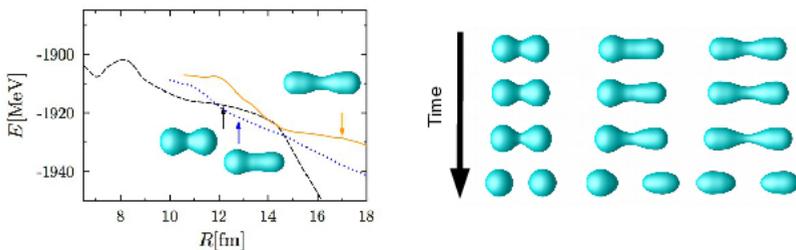


Figure 1: Left: Energy as a function of the distance between the two fragments for the three modes. The arrows represent the starting configuration of the dynamical calculation. Right : Isosurface density as a function of time for the three modes. The time between two pictures is different for the three modes, from left to right, $\Delta t = 0.675$ zs, 1.8 zs and 1.08 zs.

2.1 One-body observables

Several observables can be extracted from this simulation of the fission process. In particular, the total kinetic energy (TKE) is calculated after the complete separation of the two fragments by adding the Coulomb energy to the kinetic energy. A comparison between the TD-BCS and the experimental data is shown in fig. 2. The TD-BCS can predict neither the population of each of the mode nor the fluctuation of the TKE. Nevertheless, it predicts an average TKE and mass distribution for each mode in good agreement with the experimental distributions. For the elongated mode, it is found that this mode is compatible with the tail of the TKE distribution.

We can worry about the dependence of those observables with the starting point of the dynamic. In a naive picture, starting with a more compact shape increases the total energy and should then increase the TKE. In reality, due to the strong friction forces, all this additional energy is dissipated during the dynamic. For example, for initial distance of the fragment between 9.5 and 12.5 fm (both well before scission), the TKE is changed by less

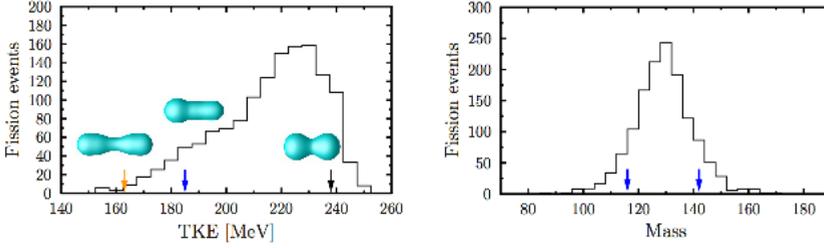


Figure 2: Left panel: Comparison between the TKE obtained for the three mode to the experimental TKE distribution. Right panel: Comparison between the average mass in the asymmetric mode to the experimental mass distribution (only events with TKE < 220 MeV are shown).

than 1 MeV for the symmetric compact mode. The fact that this observable is independent of the starting point confirms that the evolution between $R=9.5$ fm and 12.5 fm is adiabatic.

2.2 Two-body observables

The two-body observables, like the odd-even effects or the fluctuations of the mass distribution show a different behavior. To study this effect, we display on fig. 3 (left), the neutron distribution with different initial distances between the fragments. The distribution is obtained using the projection technique developed for TDHF in ref. [13] and extended to the case with pairing in ref. [14].

Starting from a configuration close to the scission point ($R=12.5$ fm), the neutron distribution shows an odd-even effects due to the pairing correlations. When more compact initial shapes are chosen, the odd-even effects are smoothed out. This effect can be understood simply by the fact that the initial energy is larger for compact shape. Then more energy is dissipated during the descent of the potential. This dissipated energy break the pair correlation and so the odd-even effects are reduced.

We next investigate the impact of the initial configuration on the width of the fragment mass distribution in fig. 3 (right). The fluctuations of the mass distribution is obtained without pairing with the TDHF theory and is compared to fluctuation obtained with the time-Dependent Random Phase Approximation (TDRPA) theory [15,16]. The mass distribution is shown in fig. 3 (right) assuming a gaussian shape. The TDRPA goes beyond the TDHF approach with a variational approach not only for the one-body

observables but also for the fluctuations. The TDRPA result is then closer to the experimental data. Nevertheless, for the two theories a dependence of the results with the initial distance is found.

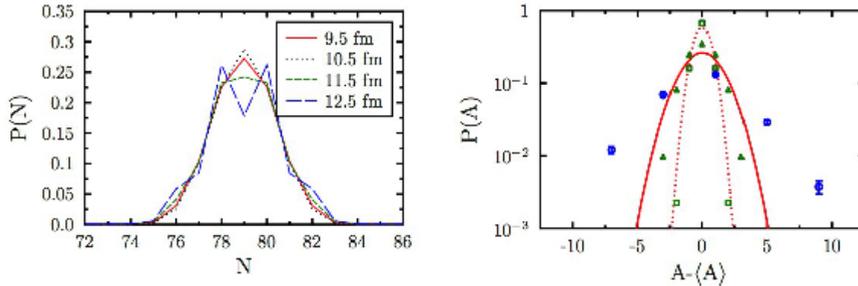


Figure 3: Left panel: Neutron distribution of the symmetric compact mode for different initial distances between the fragments. Right panel: Mass distribution obtained with TDHF (for ^{264}Fm) with initial distance $R = 10$ fm (triangles) and $R = 12$ fm (squares). The TDRPA results are shown by solid line for $R = 10$ fm and dotted line for $R = 12$ fm assuming a Gaussian distribution. The experimental mass distribution (for ^{258}Fm) is also shown with blue circles.

This is expected as the fluctuations accumulate along the entire fission path from the compound nucleus to scission. We can expect that a dynamical theory starting from the initial well would reproduce the experimental fluctuation. Nevertheless as shown in ref. [17,18], within mean-field dynamics theories, the fission process does not occur for too compact shape.

3 Conclusion

The fission process has been study with the TD-BCS theory. It is shown that the one-body observables does not depends of the initial adiabatic configuration and reproduce the experimental data. For the two-body observables, a dependence is found. The latter could be due to the non-consideration of the initial excitation energy in the dynamical calculations. This dependence shows the necessity to go beyond the present approach with finite temperature calculations.

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