COLLECTIVITY IN SMALL AND LARGE AMPLITUDE MICROSCOPIC MEAN-FIELD DYNAMICS*

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The time-dependent energy density functional with pairing allows to describe a large variety of phenomena from small to large amplitude collective motion. Here, we briefly summarize the recent progresses made in the field using the TD-BCS approach. A focus is made on the mapping of the microscopic mean-field dynamics to the macroscopic dynamics in collective space. A method is developed to extract the collective mass parameter from TD-EDF. Illustration is made on the fission of ^{258}Fm. The collective mass and collective momentum associated to quadrupole deformation including non-adiabatic effects is estimated along the TD-EDF path. With these information, the onset of dissipation during fission is discussed.

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1. Introduction

Recently, an effort has been made to give a unified description of small and large amplitude collective motion within the microscopic time-dependent energy density functional (TD-EDF) theory. The inclusion of pairing effects in nuclear dynamics has opened new perspectives for the description of giant resonances [1, 2] or direct reactions like nucleon transfer [3]. Quite recently, the possibility to get physical insight on the fission process using microscopic transport models has been revisited including pairing [4, 5] or not [6–8].

In the present article, some aspects of fission are discussed using the recently developed TD-BCS model.

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2. Fission dynamics with TD-BCS

The TD-BCS approach is a microscopic method that solves the evolution of quasi-particle states in their self-consistent mean-field and pairing field. Technical aspects related to the TD-BCS we are using are extensively described in Refs. [3, 9, 10]. Some great advantages of this approach is that:

(i) It allows to treat nuclear dynamics from small to large amplitude collective motion.

(ii) It does not pre-select *a priori* specific collective degrees of freedom (DOFs). As a matter of fact, any collective DOF can play an important role as soon as it can acquire non-zero value consistently with the symmetries of the initial condition.

(iii) It does not presuppose that the collective motion is adiabatic or not. In the context of fission, it is still quite useful to first consider the adiabatic energy landscape as a function of some collective DOFs, like elongation, multipole moments, *etc.*

An illustration is given in Fig. 1 for the case of ^{258}Fm fission. This curve is obtained here using the static version of TD-EDF with various constraint on the quadrupole moment. In the limit of very slow fission, it is expected that the dynamics directly reflects the motion along the adiabatic path. However, starting from one of the point in the curve, there is no reason that the TD-EDF evolution follows this energy landscape. Indeed, the motion can eventually be rather fast especially close to the scission point where the slope of the energy landscape change abruptly. The motion can be more

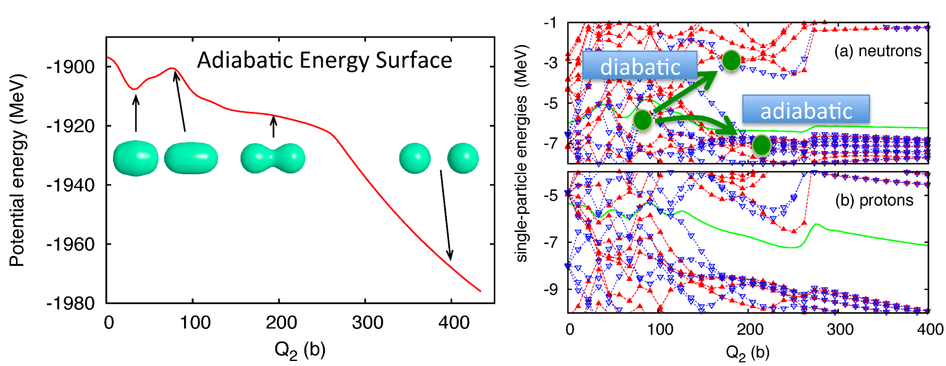

Fig. 1. (Color on-line) Left: Adiabatic potential energy curve obtained for the case of compact symmetric fission in ^{258}Fm. The corresponding neutron and proton single-particle energies are shown in the right part. See Refs. [4, 5] for details. The two extreme cases of adiabatic and diabatic motions are illustrated close to level crossing.

complex than a collective motion in one dimension due to the possibility to excite other DOFs. The departure from adiabatic motion can directly be observed in the evolution of the nucleus density in TD-EDF (see Fig. 2). We see in this figure that the two nuclei after scission can exhibit large octupole deformation. Such deformations are not observed along the adiabatic path.

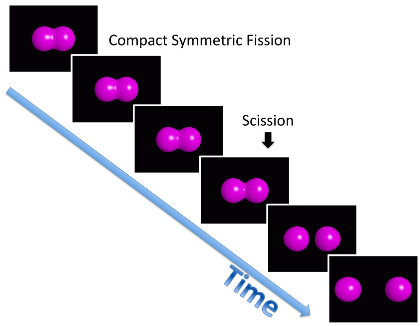

Fig. 2. (Color on-line) Illustration of the density profiles obtained with TD-EDF at different time of the fission process.

3. Collective aspects of mean-field dynamics

To further study some aspects of fission with TD-EDF and make connection with macroscopic models, it is highly desirable to be able to define collective masses and momenta associated with a set of degrees of freedom. A method has been proposed in Ref. [5]. In general, the collective variable under interest $\hat{Q}$ is known explicitly (multipole moments, relative distance, mass asymmetry, neck, *etc*). Less easy is the knowledge of the associated collective momentum $\hat{P}$ and associated mass M. Several methods based on adiabatic approximation are usually used to construct these quantities. Here, we directly deduce them from TD-EDF evolutions.

Assuming that the collective variable is local, and that the conjugated variables should fulfill the two conditions

$$\left\langle [\hat{Q}, \hat{P}] \right\rangle = i\hbar \tag{1}$$

and

$$\frac{d\langle \hat{Q} \rangle}{dt} = -\frac{i}{2\hbar m} \mathrm{Tr}\left(\left[Q, p^2 \right] \rho(t) \right) \equiv \frac{\langle \hat{P} \rangle}{M} \,, \tag{2}$$

it was possible to prove that the collective momentum can be written as

$$P \equiv -i\hbar \frac{M}{m} \left(\frac{\nabla^2 Q}{2} + \nabla Q \cdot \nabla \right) . \tag{3}$$

Here, the collective mass M is given by

$$\frac{1}{M(t)} = \frac{1}{m}\mathrm{Tr}\left[\rho(t)\nabla Q \cdot \nabla Q\right] . \quad (4)$$

This expression of the mass is sometimes also obtained in other approaches that specifically assume adiabatic or diabatic motion. The great difference stems from the fact that here the density $\rho(t)$ entering in it is the TD-EDF one.

For instance, a similar mass formula is found in the context of giant resonances using a scaling assumption (see, for instance, [11]), then the one-body density identifies with the ground state density. This expression is also obtained in the context of di-nuclear system [12] where small amplitude limit is not assumed. In the latter case, it was shown that the above formula can eventually lead to the standard adiabatic Cranking approximation if a slow motion in collective space is assumed. It is finally interesting to mention that the present expression for the mass and the present method differ from the other ones due to the nature of the density entering in Eq. (4). The density is directly the TD-EDF one and can contain non-adiabatic effects as well as possible influence of other collective and non-collective DOFs. The method we used to define collective mass and momentum is very general. As far as the mass and collective momentum are concerned, we do not assume, for instance, a decoupling of the single-particle and collective states as it is sometimes assumed in microscopic models [13, 14], we just use the fact that the collective operator Q is a one-body operator. Such assumption of at least

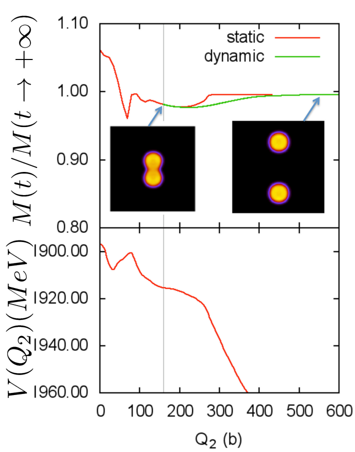

Fig. 3. (Color on-line) Top: Evolution of the collective quadrupole mass along the adiabatic path (solid black/red) and along the TD-EDF path (solid gray/green). Bottom: The corresponding position in the PES is recalled.

partial decoupling would be, however, necessary to obtain the non-adiabatic potential energy landscape associated to the TD-EDF method as was tried in Ref. [5, 15].

An illustration of the quadrupole collective mass obtained with the TD-EDF method is shown in Fig. 3. For comparison, the mass obtained assuming that the density identifies with the density along the adiabatic path is shown. While at initial instants, the system follows the adiabatic limit, when it approaches the scission, the collective motion accelerates and clear deviation from adiabaticity is observed.

4. Dissipated energy along the fission path

The possibility to access collective momentum is useful to get information on the energy balance during fission. In particular, it can give access to some dissipative aspects. We show in Fig. 4 examples of evolution of the quadrupole momentum for different initial conditions taken for initial values of Q_2 lower or greater than the scission point $Q_2^{\rm sc}$. The most important feature is that, for $Q_2 \leq Q_2^{\rm sc}$, all curves seem to become identical before reaching scission. This could only be understood assuming that the system is strongly damped at the early instant of its dynamical evolution and rapidly ends up along the same dynamical path. It is worth mentioning that this path does not necessarily match the one displayed in Fig. 1.

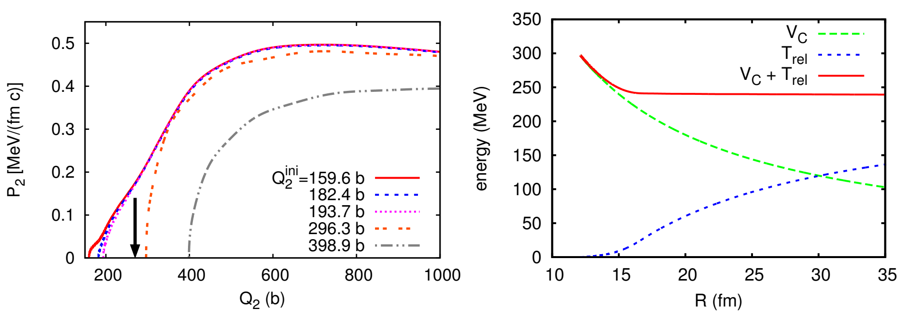

Fig. 4. (Color on-line) Left: Evolution of the collective quadrupole momentum as a function of the Q_2 for different initial conditions. Right: Energy balance between the kinetic energy associated to the relative motion of fissioning fragments and Coulomb energy. The sum of the two quantities is shown to saturate to the final total kinetic energy after scission point.

Starting from this finding and from the knowledge of the collective momentum, it was possible to extract the total energy dissipated along the fission path [5]. It was shown that this dissipated energy is quite large and can approach 10% of the final total kinetic energy TKE of the daughter nuclei after fission. The TKE obtained in the symmetric compact fission of

^{258}Fm is shown in right panel of Fig. 1 and is close to 200 MeV. Therefore, about 20 MeV of the initial energy is dissipated during the fission. In the present calculation, this energy is transferred to other internal DOFs of the two fissioning nuclei and can eventually lead to particle evaporation.

5. Summary

In the present article, we have illustrated the fission of a superfluid nucleus using the TD-BCS approach. A method is used to get macroscopic information, like collective momentum and mass from the microscopic evolution. In particular, it is shown that the collective mass deviates from the adiabatic limit, especially close to the scission point where the evolution is faster. The sharing of the initial energy between total kinetic energy of final fragments and internal excitations is also studied. It is seen that almost 10% of the TKE was dissipated. This dissipation occurs at the very first instants of the dynamical evolution.

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