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Pairing effects in nuclear dynamic

Denis Lacroix[1], Guillaume Scamps[2] and Yusuke Tanimura[1]

[1]Institut de Physique Nucléaire, IN2P3-CNRS, Université Paris-Sud, F-91406 Orsay Cedex, France
[2] Department of Physics, Tohoku University, Sendai 980-8578, Japan.

Abstract

In recent years, efforts have been made to account for super-fluidity in time-dependent mean-field description of nuclear dynamic [1–5]. Inclusion of pairing is important to achieve a realistic description of static properties of nuclei. Here,we show that pairing can also affect the nuclear motion. State of the art TDHF approach can describe from small to large amplitude collective motion as well as the collision between nuclei. Very recently, this microscopic approach has been improved to include pairing either in the BCS or HFB framework. Recent applications of the 3D TDHF + BCS (TDHF+BCS) model introduced in [4] will be presented. The role of super-fluidity on collective motion [6, 7], on one- and two-particle transfer [8] and on fission [9, 10] will be illustrated.

1 Introduction

Nuclear time-dependent mean-field based on the energy density functional approach is experiencing nowadays a renewal of interest [11–16]. In particular, it allows one to describe a wide variety of dynamical processes ranging from small to large amplitude collective motions, including nuclear reactions. Recently, the inclusion of pairing correlations in Time-Dependent Energy Density Functional Theory (TD-EDF) has opened new perspectives [1–5]. The possibility to describe pairing in dynamical models is an important step in the field since (i) it allows to describe dynamical processes involving superfluid nuclei, that are the majority of nuclei in the nuclear chart; (ii) it opens the perspective to uncover expected or new dynamical phenomena emerging from pairing dynamics. It is indeed well known, especially in condensed matter that the occurrence of Cooper pairs can lead to new macroscopic effects like the occurrence of Josephson effect or vortex dynamic [17].

In this proceedings, we highlight recent progresses in the field and illustrate through applications how superfluidity can affect the nuclear motion either at the level of one nucleus or when two nuclei are involved like during Heavy-Ions collisions.

2 TD-EDF with pairing

The TD-EDF with pairing generalizes the usual TD-EDF by propagating in time both the normal and anomalous densities ρ and κ. These two densities are defined through

$$\rho_{ij}(t) = \langle \hat{a}^\dagger_j \hat{a}_i \rangle, \quad \kappa_{ij}(t) = \langle \hat{a}_j \hat{a}_i \rangle,$$

where $(\hat{a}^\dagger_i, \hat{a}_i)$ correspond to creation/annihilation operators of a complete set of single-particle states. The TD-EDF equation of motion are similar to the TDHFB ones and can be written as (see for instance [18, 19]):

$$i\hbar \frac{d}{dt}\rho = [h(\rho), \rho] + \kappa\Delta^* - \Delta\kappa^*, \tag{1}$$

$$i\hbar \frac{d}{dt}\kappa = h(\rho)\kappa + \kappa h^*(\rho) - \rho\Delta - \Delta\rho^* + \Delta. \tag{2}$$

Here $h(\rho)$ and Δ are respectively the mean-field and pairing field matrix. These operators can be generically written as:

$$h(\rho)_{ij} = \left(\frac{p^2}{2m}\right)_{ij} + U_{ij}(\rho) = \left(\frac{p^2}{2m}\right)_{ij} + \sum_{kl} v^M_{ikjl}\rho_{lk} \tag{3}$$

$$\Delta_{ij} = \frac{1}{2}\sum_{kl} v^P_{ijkl}\kappa_{kl}. \tag{4}$$

where U is the mean-field potential. Here v^M and v^P denote effective vertex respectively in the particle-hole and particle-particle channels and can be directly defined as functional derivative of the energy. In the nuclear context, the difference between TDHFB and TD-EDF stems from the flexibility in choosing the effective interactions.

Pairing will affect both the evolution of one-body macroscopic variables and their fluctuations in the following way:

- **Pairing effect on one-body evolution.** Let us consider a collective one-body degree of freedom $\hat{Q} = \sum_{ij} \langle i|\hat{Q}|j\rangle \hat{a}_i^\dagger \hat{a}_j$. Its evolution is obtained through:

$$
\begin{aligned}
i\hbar \frac{d\langle \hat{Q}\rangle}{dt} &= i\hbar \mathrm{Tr}\left(Q \frac{d\rho}{dt} \right) \\
&= \mathrm{Tr}\left(Q[h(\rho), \rho] \right) + \mathrm{Tr}\left(Q[\kappa\Delta^* - \Delta\kappa^*] \right). \\
&= \mathrm{Tr}\left(Q[h(\rho), \rho] \right)
\end{aligned}
$$

  The fact that the pairing field disappears in the last line has been proved in [10] for local pairing interaction. This does not however mean that pairing does not affect one-body motion. Indeed, pairing directly change the one-body density matrix property, and ultimately the expectation value $\langle \hat{Q}\rangle = \mathrm{Tr}\left(Q\rho(t) \right)$.

- **Pairing effect and correlations.** A more direct evidence of pairing effects is on two-body correlations. Indeed, considering the fluctuation of the observable $\hat{Q}$, we have:

$$
\begin{aligned}
\sigma_Q^2 &= \langle \hat{Q}\hat{Q}\rangle - \langle \hat{Q}\rangle\langle \hat{Q}\rangle = \sum_{ijkl} \langle i|\hat{Q}|j\rangle \langle k|\hat{Q}|l\rangle \left(\langle a_i^\dagger a_j a_k^\dagger a_l\rangle - \langle a_i^\dagger a_j\rangle \langle a_k^\dagger a_l\rangle \right) \\
&= \mathrm{Tr}(Q\rho Q(1-\rho)) + \sum_{ijkl} \langle i|\hat{Q}|j\rangle \langle k|\hat{Q}|l\rangle \kappa_{ki}^* \kappa_{lj} \qquad (5)
\end{aligned}
$$

  where the first term is the standard expectation value in Fermi system when pairing is neglected, while the second term is directly due to pairing. Due to pairing correlation two-body correlation are expected to be enhanced.

In the following, we will illustrate either the influence of pairing on one-body evolution (on vibration and fission) or directly on correlations (two-particle transfer).

3 Small amplitude vibrations

The inclusion of pairing correlations significantly extends the domain of applicability of TD-EDF. First, it allows to describe ground state properties of many nuclei in the nuclear chart rather reasonably. In particular, deformation properties of the ground state is better accounted for compared to the EDF theory without pairing. The TD-EDF with BCS approximation for pairing offers a rather versatile alternative approach to QRPA especially to

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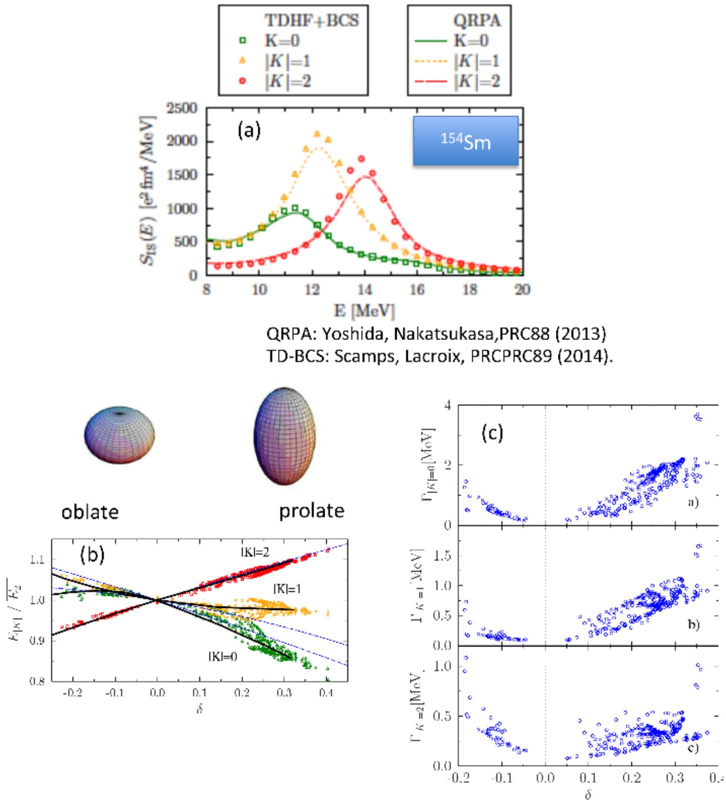

Figure 1: Giant quadrupole collective motion described with TD-EDF including pairing. (a) Comparison between the time-dependent calculation (called in the figure TDHF-BCS) and the QRPA response of ref. [20]. (b) Systematic study of the giant quadrupole energy splitting due to deformation. Each point in this figure corresponds to one nucleus with a given value of the deformation parameter δ (for more details see [6]). The lines correspond to the result of a hydrodynamical model [21] including deformation and coupling to the Giant Monopole Vibration. (c) Width of the three quadrupole response functions depending on the quadrupole moment projection of the excitation operator. Again each point corresponds to a nucleus with a given deformation δ.

study axially deformed nuclei or nuclei with triaxial deformation. Recently, the isoscalar (IS) and isovector (IV) Giant Quadrupole Response (GQR) of more than 700 nuclei has been systematically investigated in Refs. [6, 7]. Important information can be inferred from these studies:

- First, the TD-EDF gives results that are consistent with QRPA even if the BCS approximation is used in the former while the full Hartree-Fock Bogolyubov theory is implemented in the latter (see panel (a) of Fig. 1). With symmetry unrestricted codes, nuclei without specific axis of symmetry that still challenge state of the art QRPA codes, can also be studied without additional difficulty compared to axially symmetric nuclei.
- The effect of deformation on the splitting of isoscalar GQR has been specifically studied. This splitting is well reproduced by the hydrodynamical model of Ref. [21] and essentially depends on the initial deformation as well as the coupling to the isoscalar giant monopole motion (see panel (b) of Fig. 1).
- The TD-EDF as well as the QRPA theories are globally able to describe the energy of the first low-lying 2^+ state but fails to reproduce its collectivity.
- The TD-EDF approach is unable to describe the life-time (width of the response) in spherical nuclei, even if pairing is included. As it is well known, damping mechanisms require to include the coupling to complex internal degrees of freedom. As a matter of fact, see panel (c) of Fig. 1, the width of the response significantly increases as the deformation increases. Interestingly enough, at large deformation, the fragmentation obtained in strongly deformed nuclei seems compatible with the experimental width. Therefore, as far as the damping width is concerned, a transition seems to occur between spherical nuclei, where correlations dominate, to deformed nuclei, where one-body dissipation seems to dominate.

4 Fission dynamic

One obvious advantage of the time-dependent simulation is that, contrary to the linear response theory, it can be applied to situations with strong external perturbations or when the nucleus encounters very large deformations. Larger amplitude motion in heavy systems like the fission process

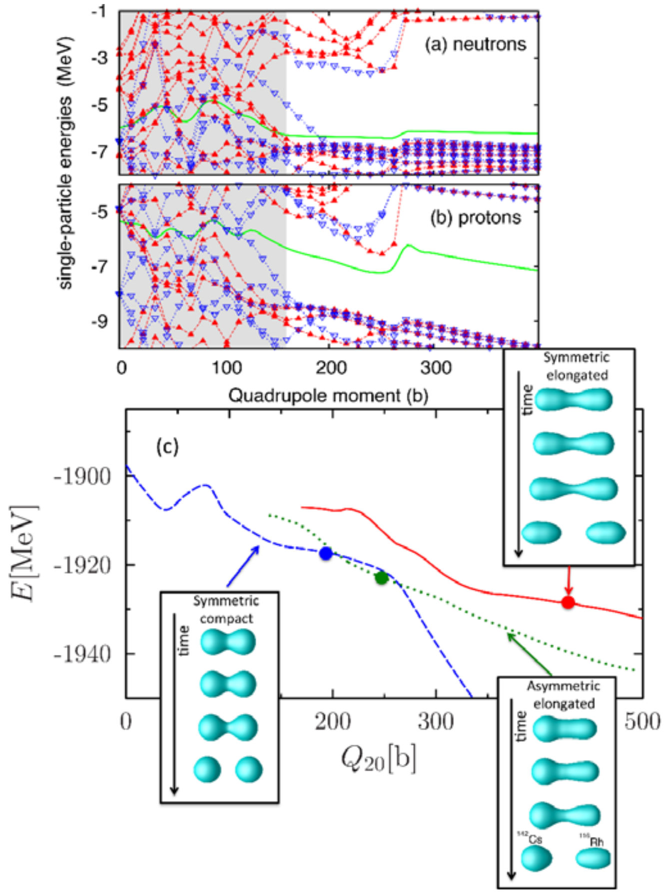

Figure 2: (Color online) Simulation of different fission paths in ^{258}Fm with TD-EDF including pairing. Evolution of neutron (a) and proton (b) single-particle energies along the adiabatic path (symmetric compact case). The red closed and blue open triangles correspond respectively to positive and negative parity states. The thick green lines represent the Fermi energies. (c) Adiabatic surfaces corresponding respectively to three different paths: symmetric compact (blue dashed line), symmetric elongated (red solid line) and asymmetric elongated (green dotted line). The three insets correspond respectively to three non-adiabatic evolutions obtained using TD-EDF. In the three cases, the starting point corresponds to the filled circles indicated in the corresponding adiabatic curve. See Ref. [9] for details.

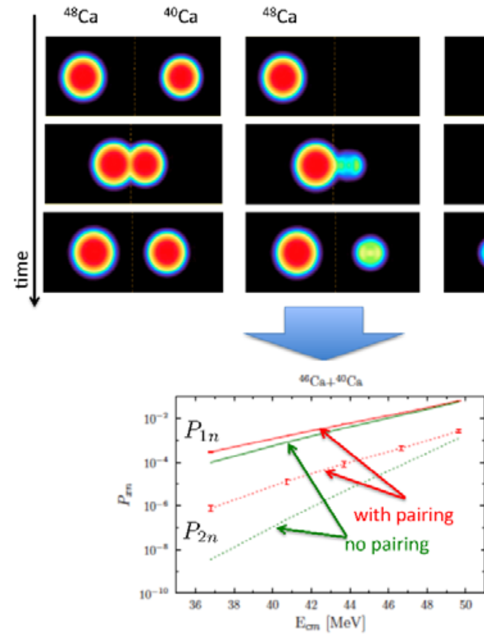

Figure 3: Illustration of the transfer process for a central collision ^{40}Ca + ^{48}Ca with energy below the Coulomb barrier. Top: snapshot of the density at different time of the reaction. Top-left: the density of the two nuclei are shown. Top-Middle (resp. Top-Right): the density of nucleons initially in the ^{48}Ca (resp. ^{40}Ca) and eventually transmitted to the other nucleus are shown. Bottom: probability to transfer one P_{1n} or 2 nucleons P_{2n} as a function of the center of mass energy for the reaction ^{40}Ca + ^{46}Ca, the latter nucleus being superfluid.

can be studied using the TD-EDF. However, as pointed out soon after the introduction of this approach in nuclear physics [22, 23], this problem is difficult to address in a mean-field theory. This stems from the coexistence of quantum effects in both single-particle and collective space (see for instance the recent review [24]). The description of fission passes through the proper treatment of quantum tunneling in many-body system, spontaneous symmetry breaking, non-adiabatic effects,... In spite of this complexity, this problem has recently been revisited in a recent series of works [9, 10, 25–27]. An illustration of different fission paths in ^{258}Fm is shown in Fig. 2 (adapted from Refs [9, 10]). A clear advantage of quantal microscopic transport theory is that they consistently include nuclear structure and dynamical effects. In particular, they do not rely on the assumption that the motion is adiabatic. It was shown recently, that experimental observation are compatible with a slow and nearly adiabatic motion before scission and a mean-field+pairing like dynamics around the scission point [9]. Work is actually underway to connect microscopic mean-field theory and macroscopic transport properties [10].

5 Binary collisions below the Coulomb barrier

One interest of time-dependent EDF approach is that it allows to treat a single nucleus or binary systems in a unified framework. We summarize below some recent results obtained when describing collisions of superfluid nuclei. More precisely, central collisions below the Coulomb barrier have been considered. This study was motivated by the recent experimental observation of the 1 particle, 2 particles and 3 particles transfer probabilities, denoted hereafter by resp. P_{1n}, P_{2n} and P_{3n} [28].

In Ref. [8], the increase of two particles transfer due to pairing correlation has been carefully analyzed. An illustration of results obtained for the reaction ^{40}Ca + ^{46}Ca at various beam energy is given in panel (b) of Fig. 3. In this reaction, the nucleus ^{46}Ca has initially non-zero pairing while ^{40}Ca is in a normal phase. To extract multi-nucleon transfer probabilities, specific method based on particle projection should be used [8, 29]. In this figure, we see that the inclusion of pairing or not affects both one-particle and two-particle transfer. Indeed, the one-particle transfer is affected by pairing in particular due to non-zero occupation of single-particle states above the Fermi energy. In the two-particle transfer channel, a strong enhancement is observed due to pairing, as expected. In ref. [8] it was shown that the enhancement is directly proportional to the initial pairing gap in the superfluid nucleus. Application of the TD-BCS approach to the reaction considered experimentally in Ref. [28] was also made. Two important conclusions were drawn (i) The theoretical results obtained with the dynamical theory are compatible with those reported in Ref. [28] where a static BCS approach coupled to a semi-classical model for reaction has been used. It is worth mentioning that, the TD-BCS theory treats both structure and reaction on the same footing and does not a priori make truncation on possible important excited states during the transfer. (ii) A second important conclusion is that the inclusion of pairing is not sufficient to explain the enhancement of 2 nucleon transfer and other effects should be invoked.

6 Conclusion

We presented here most recent applications of TD-EDF including pairing correlation. In recent years, it was demonstrated that pairing can be accurately incorporated in quantum transport theories. This has opened the possibility to describe realistically the evolution of superfluid nuclei all along the nuclear chart including the heaviest ones. When the BCS approximation is made, a rather versatile and computational friendly approach is obtained leading to a unified description of many processes in nuclei from small to large amplitude collective motion.

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