

Effect of pairing on transfer and fusion reactions

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Abstract. In the present contribution, the effect of pairing on nuclear transfer and fusion reactions close to the Coulomb barrier is discussed. A Time-Dependent Hartree-Fock + BCS (TDHF+BCS) microscopic theory has been developed to incorporate pairing. One- and two-particle transfer probabilities can be obtained showing the importance of pairing. The calculated transfer probabilities are compared with the recent experimental results obtained for the $^{96}\text{Zr}+^{40}\text{Ca}$. Reactions involving the ^{18}O with lead isotopes are also presented, that are also of current experimental interest. Finally, a study of the fusion barrier height predicted with the TDHF+BCS theory is compared with the experimental values for the $^{40,44,48}\text{Ca}+^{40}\text{Ca}$ reactions.

1 Introduction

Pairing correlations are known to play an important role in the structure of the nucleus. It is nowadays an important challenge to take into account for the pairing correlations in state of the art microscopic transport theories [1–4]. Recently, it was shown that pairing has a non negligible effect on the description of giant resonances [5, 6] in particular to provide realistic properties (deformation, single-particle state fragmentation around the Fermi energy, ...) for nuclear ground state on top of which collective excitation can be built up. These properties are also expected to be important to describe nuclear collisions. The goal of this study is to illustrate how pairing influences the transfer and fusion processes.

The natural way to incorporate pairing into a mean field dynamic, is to extend Time-Dependent Hartree-Fock theory by introducing a quasi-particle picture. This leads to the so-called Time-dependent Hartree-Fock-Bogoliubov (TDHFB) approach. This approach, while formally very attractive, still requires too much numerical effort to be applied on a large scale [1, 3]. A good compromise able to grasp most aspects of pairing correlations while keeping the numerical simulation reasonable, is to consider its simplified TDHF+BCS limit [2, 7]. Recently, this approach has been applied to nuclear collision at energy close or below the Coulomb barrier. In the present work, new comparisons with recent experiments are made. All details of the calculations are given in the Ref. [5]. In the section 2, we study the transfer reaction and in the section 3, the influence of pairing on the fusion barrier is discussed.

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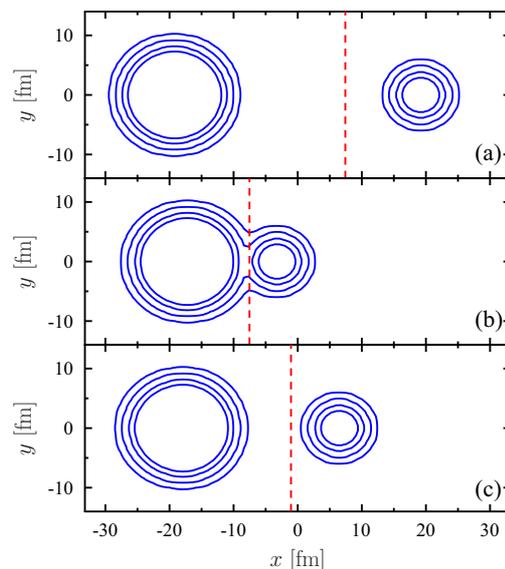


Figure 1. Evolution of the total density projected on the x reaction plane for the central collision $^{208}\text{Pb}+^{18}\text{O}$. The center of mass energy is 71.88 MeV. The panels (a), (b) and (c) correspond respectively to the time $t=0$ s, $t=13.5\times 10^{-22}$ s and $t=27\times 10^{-22}$ s. The neck position is indicated by the dashed vertical line in each panel.

2 Transfer Reaction

One of the motivation of our study is the recent renewal of interest in transfer reactions below the Coulomb barrier, like the reaction $^{96}\text{Zr}+^{40}\text{Ca}$ [8]. With the specific detectors setup used in this experiment, a rather clean extraction of multi-nucleon transfer probabilities have been obtained. In particular, a strong enhancement of the two-particle transfer probabilities was found with $P_2 \approx 3P_1^2$. Here P_2 and

P_1 are respectively the one- and two-neutrons transfer. In the absence of correlation, quantum and fermionic effects, one simply expects a sequential transfer with $P_2 \approx P_1^2$. The TDHF calculation [9–11], gives a similar relation due to the independent particles picture. In order to understand how pairing can lead to an enhancement of P_2 , the TDHF+BCS theory has been applied to this reaction.

In our microscopic model, the two nuclei are first separately initialized in their ground states with the Hartree-Fock plus BCS theory with the Skyrme functional Sly4d and a mixed contact type pairing interaction [12]. Then the two nuclei are positioned on a lattice with given initial velocities. The position and initial velocities are chosen to properly describe a given beam energy E_B and impact parameter b . One of the advantage of the experiment [8] is that it can be simulated using zero impact parameters only, that greatly simplifies the theoretical description (see discussion below). An example of density evolution below the Coulomb barrier for a central reaction $^{208}\text{Pb}+^{18}\text{O}$ is presented in Fig. 1. At this energy, the two nuclei approaches (a), can exchange particles during the contact (b) and re-separates (c).

2.1 The $^{96}\text{Zr}+^{40}\text{Ca}$ reaction

The transfer probabilities of Ref. [8] have been presented in terms of the minimal distance of approach D . Assuming a Rutherford trajectory, a simple relation between the center of mass energy $E_{c.m.}$ and D is obtained,

$$D = \frac{Z_P Z_T e^2}{2E_{c.m.}} \left(1 + \frac{1}{\sin(\theta_{cm}/2)} \right) \quad (1)$$

with Z_P and Z_T the target and projectile proton numbers while θ_{cm} is the center of mass scattering angle. If we assume that the transfer probabilities depend only on the distance of closest approach, a comparison between theory and experiment can be made by performing several TDHF+BCS simulation where the beam energy is varied.

To extract the transfer probabilities from TDHF+BCS the double projection technique, that project out onto given neutron/proton numbers in the quasi-target and/or quasi-projectile after the reaction is used [13]. The results are shown in Fig. 2 for the reaction $^{96}\text{Zr}+^{40}\text{Ca}$ and compared with the experimental data as well as to the theoretical calculations presented in Ref. [8]. As we can see, the one-particle transfer probability is slightly overestimated in our calculation. As mentioned in the Ref. [8], the probability to transfer one neutron depends of the single particle energies and of the fragmentation of the occupation numbers. Here, no parameter are adjusted to experimental data in our calculations and the difference in P_{1n} certainly stems from the location of single-particle levels around the Fermi energy obtained in the mean-field approach that differs from the one used in Ref. [8].

The situation is different for the probability to transfer two neutrons. The results found by the TDHF+BCS theory is below the experimental data by a factor 4 at 90 MeV while only 15 % of the probability is missed at 93 MeV. Note that the situation is better compared with the

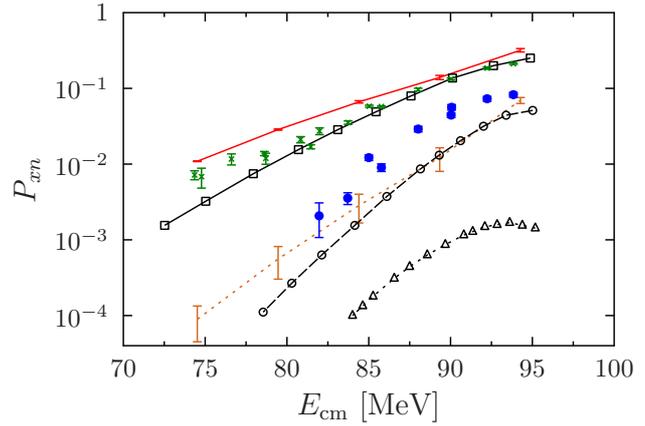


Figure 2. Transfer probabilities as a function of the center of mass energy for the reaction $^{96}\text{Zr}+^{40}\text{Ca}$. The experimental data extracted from [8] are represented by full circles for P_2 and crosses for P_1 . The TDHF+BCS results are displayed by red solid line for the probability to transfer one neutron and by orange dashed line for the probability to transfer two neutrons. In this figure, we also report the theoretical results obtained in Ref. [8] where a shell model calculation + semi-classical treatment of the reactions have been used. The results are respectively shown by squares for the transfer of one neutron, triangles for the probability to transfer two neutrons if the only retained channel is the ground state to the ground state transfer. The open circles correspond to the two neutrons transfer where not only the GS to GS but also GS to first excited state transfer is accounted for.

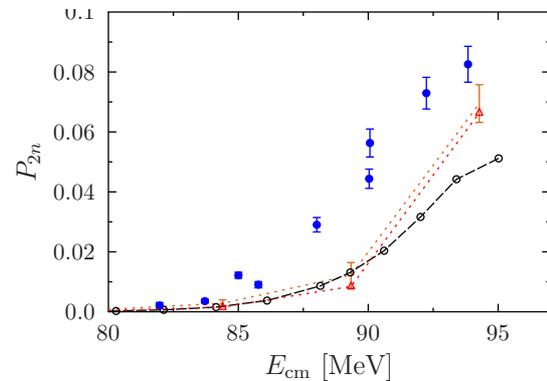


Figure 3. Same as Fig. 2 in linear scale for the two neutrons transfer probability. The results of P_{2n} obtained by neglecting the anomalous density is also shown by red triangles.

case where the anomalous density is neglected. For this reaction, we do not show the results of TDHF, because the ^{96}Zr in the Hartree-Fock theory, is found to be have an octupolar deformation in its ground state. To get a more quantitative view of the missing probabilities as well as of the difference between our results and the theoretical calculations given in ref. [8], the two-particle transfer probabilities are shown in linear scale in Fig. 3. from this figure, we can see that:

- the two theoretical calculations are globally in agreement. This is an interesting point since two completely different strategies are used. In our calculation, structure

and dynamical effects are included in a unified approach while in Ref. [8], static properties are obtained using nuclear structure models including pairing while the nuclear reaction part is treated separately. Nevertheless, the two approaches are consistent with each others.

- We see that our approach predicts slightly higher P_{2n} especially at high beam energy. It should be noted, that no selection of channels is made in TDHF+BCS, in particular, we do not restrict the transfer to the ground state or to the first excited state. The enhanced P_{2n} plaid in favor of transfer to states at higher excitation energy that have been omitted in Ref. [8].
- Pairing correlations enters both through the non-zero value of the anomalous density components and through the fragmentation of single-particle states. The enhancement of two-particle transfer is mainly due to the latter effect leading to a reduction of the Pauli exclusion principle during transfer. This is illustrated in Fig. 3 where the red triangle gives the results when the anomalous density is set to zero while keeping the BCS occupation numbers fixed. The results are very close to the full case.
- Overall, we see that including pairing is not sufficient to understand the two-particle transfer and additional effects that are not included in the quasi-particle picture seems to play an important role. Among them, we could anticipate that correlations induced by the diffusion of the intrinsic state towards complex configurations and/or quantal zero point motion in collective space might play an important role. To incorporate these effects, theories beyond the quasi-particle approaches like the time dependent density matrix theory [14] or the stochastic mean-field theory [15] might be able to provide suitable tools.

3 The $^{18}\text{O}+^A\text{Pb}$ reactions

Here we study the collision between the ^{18}O and different lead isotopes. The ^{18}O nucleus is quite interesting because (i) such nuclei can be realistically used in reaction (ii) it is among the lightest nucleus that enters within the range of applicability of the Energy Density Functional approach (iii) in a simplified picture, it can be seen as a single Cooper pair out of an inert ^{16}O core. We investigate below possible effects of the change of the collision partner. Using the TDHF+BCS approach, the fusion threshold that includes possible dynamical effects can be extracted [16]. The fusion threshold is found to be at an energy of 73.85 MeV for the $^{18}\text{O}+^{206}\text{Pb}$ and 73.35 MeV for the $^{18}\text{O}+^{208}\text{Pb}$ reaction.

The one and two-particles transfer probabilities obtained for the reactions of ^{18}O with lead nuclei using the TDHF+BCS theory are shown in Fig. 4 as a function of the distance of closest approach. The theory without pairing obtained with the equal-filling approximation [13] is also shown. Similarly to previous studies, a significant enhancement of the two-particle transfer is observed when pairing correlations are accounted for.

To focus on the effect of changing the lead isotopes by 2 nucleons only, a direct comparison of the two reactions

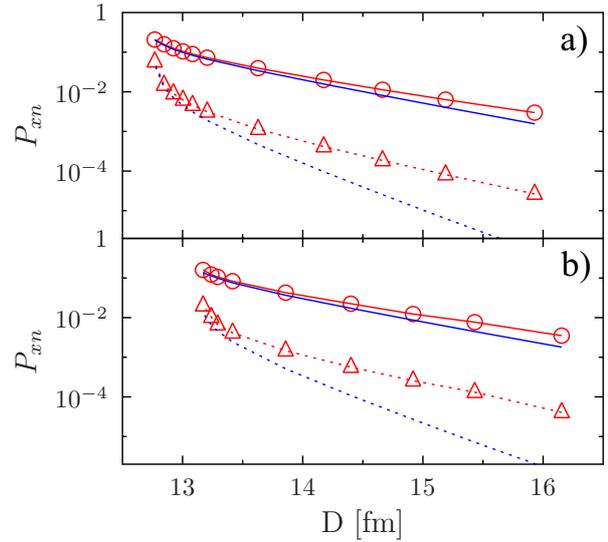


Figure 4. Neutron transfer probabilities from oxygen to lead as a function of the distance of closest approach. The two reactions are shown, panel (a) : $^{206}\text{Pb}+^{18}\text{O}$, panel (b) : $^{208}\text{Pb}+^{18}\text{O}$. The results are shown for the probabilities to transfer one neutron (triangles) and two neutrons (circles). The results without pairing is also shown with solid and dashed line respectively for the probability to transfer one and two neutrons.

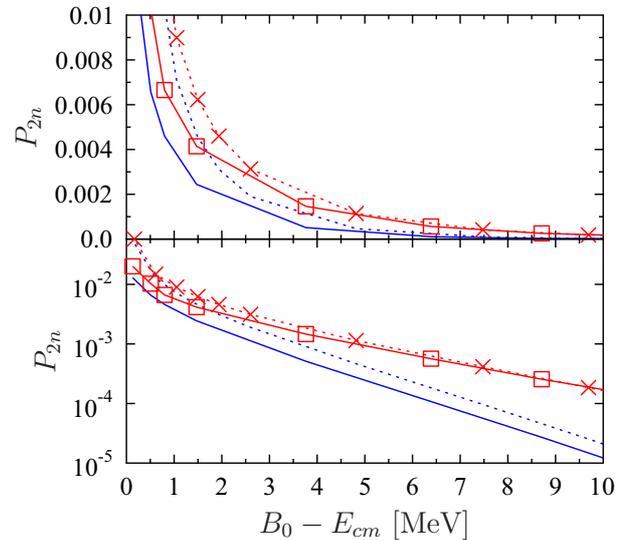


Figure 5. Two-neutron transfer probability as a function of the energy below the barrier for the reaction $^{208}\text{Pb}+^{18}\text{O}$ (solid lines) and $^{206}\text{Pb}+^{18}\text{O}$ (dashed lines). The results with the pairing are shown with crosses and squares and the results without pairing are shown by solid and dashed lines.

considered here is shown in fig. 5. We see on this figure that with the equal-filling approximation, the probability of two neutron transfer is systematically larger by a factor 2 with ^{206}Pb than for ^{208}Pb . A similar situation is seen also when pairing is plugged in at high energy close to the Coulomb barrier. The lowering of pairing in ^{208}Pb com-

pared with ^{206}Pb can be anticipated from the magicity of ^{208}Pb . This magicity has two effects (1) The Q value associated to the reaction $2n+^{206}\text{Pb} \rightarrow ^{208}\text{Pb}$ is higher than the one associated to $2n+^{208}\text{Pb} \rightarrow ^{210}\text{Pb}$, due to the ^{208}Pb binding energy (ii) before transfer, no room is available in the $3p_{1/2}$ shell due to the sub-shell closure leading to an hindrance of the $2n$ transfer compared with ^{206}Pb . This illustration shows that the shell structure properties of the collision partners should be carefully understood as well in studying pairing effects on multi-nucleon transfer close to the Coulomb barrier.

4 Systematic of fusion barrier threshold

The role of pairing on fusion barrier has been systematically investigated using the TDHF+BCS approach by identifying the fusion threshold energy with the technique employed in [17]. Two effects stemming from pairing are expected to influence the barrier. First, pairing influences the ground state deformation. With pairing the nuclei tend to be spherical, this has an important effect on the fusion. The second effect is the transfer of neutrons prior to the crossing of the barrier that can modified the barrier height [18].

In order to compare with TDHF and avoid the comparison of nuclei with different shapes, we used in that case, the equal-filling approximation that consists in filling the last major shell of degeneracy Ω by a partial fractional occupation number $n = N/\Omega$ where N is the number of nucleons to distribute in that shell. This theory is referred to as the no pairing theory. Then the deviation of the results between the TDHF+BCS theory and the equal-filling theory will directly uncover genuine effects of pairing correlations on the fusion barrier height.

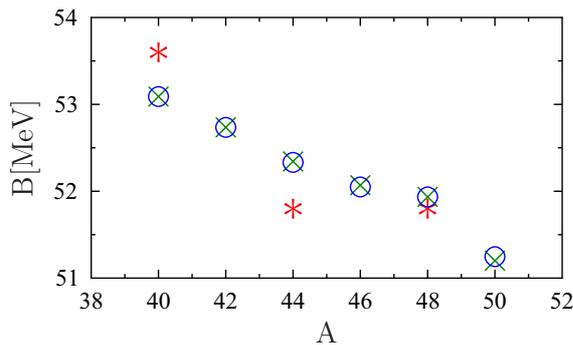


Figure 6. Fusion barrier for the $^A\text{Ca}+^{40}\text{Ca}$ reaction. The experimental barrier [19] is compared with the barrier extract from the TDHF+BCS (circles) and TDHF (crosses) calculations.

In figure Fig. 6, an illustration of fusion threshold estimated with and without pairing is shown for reactions

between different calcium isotopes. The calculation reproduces reasonably well the experimental observations. In addition, we see that pairing has almost no effect on the fusion barrier properties

5 Conclusion

In the present proceedings the effect of pairing on nuclear collisions around the Coulomb barrier is investigated. Using the TDHF+BCS approach for reactions of experimental interest we show that the main effect of pairing below the Coulomb barrier is to enhance the two particles transfer while the one-particle transfer is only slightly affected. In addition to pairing correlations, shell effects of the two collision partner can play an important role. Finally, it is shown that pairing does not affect the fusion barrier properties.

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