Heavy-ion two-particle transfer reactions as a probe of pairing correlations

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Abstract. Two-particle transfer processes induced by light and heavy ions are known to be an ideal dynamical tool for extracting information on nuclear pairing correlations. The procedure is however not unique and different reaction mechanism models (ranging from microscopic correlated successive one-particle transfer to collective macroscopic models) can be introduced to establish a link with the structural aspects of initial and final states. In the case of reactions involving weakly-bound nuclei the low-density features characterizing the vicinity of the drip line and the suggested consequent enhancement of the pairing correlations should show up as clear signature in the two-particle transfer cross sections. From a theoretical point of view in the weakly-bound case the focus is centered on the specific role of continuum states, both at the nuclear structure level, to give properly correlated wave functions, and at the reaction level, for example to treat the unbound states in the intermediate A±1 system.

If one wants to use dynamics to study pairing correlations the main road is clearly provided by two-particle transfer processes induced by light ions (reactions as (t,p), (p,t), (3He,n), (α,d)) or heavy ions, which are both exploring precisely the pair radial correlations. Unfortunately, the situation is different, for example, from low-energy one-step Coulomb excitation, where the excitation probability is directly proportional to the B(Eλ) values. Here the reaction mechanism is much more complicated and the possibility of extracting spectroscopic information on the pairing field is not obvious. The situation is actually more complicated even with respect to other processes (as inelastic nuclear excitation) that may need to be treated microscopically, but where the reaction mechanism is somehow well established.

It is often assumed that the cross section for two-particle transfer will scale with the square of the matrix element of the pair creation (or removal) operator. In this perspective in order to define and measure the collectivity of pairing modes one could compare with single-particle pair matrix elements to define some pairing single-particle units and therefore pairing enhancement factors. But the two-particle transfer process in not sensitive to just the pair matrix element. We have to look at the radial dependence of the pair transition density, which is relevant for the reaction mechanism associated with pair transfer processes. As examples we show in Figs. 1 and 2 the comparison with pure single-particle configurations in the case of the addition mode around 16O (i.e. the ground state of 18O) and the removal mode around 208Pb (i.e. the ground state of 206Pb). The comparison is done in Fig. 1 directly on the local transition density (δρP(r,r)). In Fig. 2 the comparison is done on the non-local transition density δρP(r1,r2) by fixing the
position on one particle and plotting as contour plots in space the probability of finding the second one. One immediately sees that while for pure configuration one has equal probability of finding the second particle on the same or on the opposite side with respect to the core, the pairing correlation induces a correlation in space, favouring the clustering of the pair.

\[
\rho(r_1, r_2) = |\psi(r_1, r_2)|^2
\]

\[
|\psi(r_1, r_2)|^2 = 0.8 (1d5/2)^2 + 0.6(2s1/2)^2
\]

\[
(1d5/2)^2
\]

\[
(2s1/2)^2
\]

\[
(2d3/2)^2
\]

\[
(3p1/2)^2
\]

\[
(2f5/2)^2
\]

\[
(3d1/2)^2
\]

\[
18\text{O}
\]

Figure 1. Pair transition density in \(18\text{O}\). The cases of pure \((1d5/2)^2\) and \((2s1/2)^2\) are compared with the case of correlated wave function.

Figure 2. Squared wave functions for the ground state of \(206\text{Pb}\), plotted fixing the position of one particle as a function of the position of the second one. Pure configurations are compared with the case of pairing correlated wave function.

The difficult point is to clarify how the structure properties enter into the reaction mechanism. To this end one needs reliable models for the description of the reaction mechanism. There are actually in the literature a large number of different approaches, all trying to reduce the actual complexity of the problem, which is a genuine four-body scattering (the two cores plus the two transferred particles). Note also that different approaches are used in the case of heavy-ion induced reactions (where one may need detailed information on the wave functions in both target and projectile, but on the same time the reaction is mainly surface-peaked and semiclassical descriptions may apply) and in the case of light ions (as \((p,t)\) reactions).

As an example, in a semi-microscopic approach the reaction mechanism is described as a one-step di-neutron (cluster) transfer. In this case the microscopy amounts to construct a formfactor obtained by double-folding the microscopic pair transition densities of initial and final states with some nucleon-nucleon interaction or by simple folding of microscopic pair density in the target with the one-body mean field of the projectile. Such an approach only involves the local transition densities and does not exploit the full non-local features of the pair correlation.

A fully microscopic approach is instead the one in which the two-particle transfer reaction is described by sequential two-step process (at each step one transfers one particle)\cite{1, 2}. In this case the pairing enhancement comes from the coherent interference of the different paths through the different intermediate states in (a-1) and (A+1) nuclei, due to the correlations in initial and final wave functions. Basis ingredients of the calculation are the individual formfactors for one-particle transfer and the microscopic pairing correlated wave functions. Since such fully quantal calculations are rather complex (taking into account full recoil), semiclassical approximation scheme are commonly used (although with approximate treatment of recoil).

As an example, we consider the two-particle transfer reaction \(^{208}\text{Pb}^{(18}\text{O}, ^{18}\text{O}_{gs})^{206}\text{Pb}_{gs}\), assuming that the two particles are transferred from the 3p1/2 level in \(^{208}\text{Pb}\) into a correlated ground state of \(18\text{O}\), linear combination of \((1d5/2)^2\) and \((2s1/2)^2\) (cf. Fig. 3). The effect of the
correlation on the two-particle transfer probability is evident from Fig. 4, where the result for the correlated case is compared with the corresponding value for the uncorrelated pure \((1d_5/2)^2\) case.

As we move closer or even beyond the drip lines the previous picture is inevitably modified. As schematically shown in Figs. 5-7, we move from a situation in which all relevant intermediate states are bound (Fig. 5), to situations in which only part of these states are bound (Fig. 6), finally reaching at the drip line situations in which no bound intermediate states are present (Fig. 7) and only due to the pairing interaction the \((A+2)\) system becomes bound. Typical examples are given by the so-called Borromean nuclei such as \(^{11}\text{Li}\) or \(^{6}\text{Li}\) whose ground states are bound in spite of no available bound states in \(^{10}\text{Li}\) or \(^{5}\text{He}\).

For weakly-bound systems at the drip lines it is mandatory to include in the models the positive energy part of the spectrum. If one wants to still use the same machinery used with bound states, the most popular approach is the so-called discretization of the continuum (cf.
Fig. 8). But the discretization must be used in a consistent way both in the structure and in reaction parts. All discretization procedures are equivalent as long as a full complete basis is used. In practice all procedures contain a number of parameters and criteria, that make them not all equally applicable in practical calculations. Computational constraints may in fact become a severe problem. As examples we can consider the case of HO wave functions, diagonalization in a box, the case of discretized wave functions with scattering boundary conditions (CDCC) and Gamow states (complex energies).

Figure 7. Scheme of two-particle transfer for systems at the drip line

|A=2> = \int dE X(E) [a^\dagger(E)a^\dagger(E)]_b |A>

Figure 8. Scheme of two-particle transfer with the discretization procedure

We have tested [3, 4] in simple structure and reaction models the validity and the convergence of different discretization procedures. The comparison with the exact calculations shows that descriptions based on discretization of the continuum can be accurate only when a proper choice is made of the number of discrete states, of the energy mesh and of the energy cutoff. This may imply, even in simplified cases, the use of a rather large (and unpracticable) number of channels. The use of a more restricted number of channels may lead to rather misleading results.

In particular, while energies and other observables may converge rather rapidly to the correct value, the discretization procedures normally lead to single-particle and pair wave functions characterized by with incorrect behaviours on the tail. This produces one-particle transfer formfactors which are rather different. So even if the properties of the pair wave functions seem to be well described by all methods with relatively small basis, the predicted probabilities for two-particle transfer turn out to converge only if an extremely large basis (often impossible to treat) is used. Examples will be given in a forthcoming paper [5].

In conclusion correlated sequential one-particle transfer seems to be the proper reaction mechanism present in two-particle transfer processes and to offer a formalism able to directly test the microscopic features of the pair wave functions. This implies a knowledge of the pairing states expressed in a single particle basis, since the same single-particle states enter as intermediate states in the sequential reaction process. For systems at the drip lines this means that it is mandatory a proper description of the continuum states. The discretization procedures have to be consistently used in the structure and reaction sectors, and the behaviour outside of the nuclear radii has to carefully checked, being fundamental for the description of the reaction process.

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