MACROSCOPIC FORMFACTORS FOR PAIR TRANSFER IN HEAVY ION REACTIONS

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A case is made for the use of macroscopic formfactors for nucleon pair transfer in heavy ion reactions. The formalism is based on the identification of a local pair transition density whose radial dependence can be converted in a macroscopic transfer formfactor related to the ion–ion potential in a similar way as it has traditionally been done for inelastic excitations.

Calculations of inelastic cross sections to vibrational states in heavy ion reactions have been made considerably simpler by a formulation of the excitation mechanism in terms of macroscopic variables associated with the deformation of the nuclear shape. The identification of the formfactor for nuclear excitation with the derivative of the ion–ion potential has proved to be extremely helpful in the analysis of inelastic scattering data [1]. Once the elastic cross section is satisfactorily accounted for in the optical model picture one can, in a straightforward way, proceed on to the analysis of inelastic scattering. This macroscopic description has the additional advantage of bringing forward in an automatic way the rather involved influence of all other open channels over the particular excitation under consideration.

We note that it is also possible to calculate the inelastic matrix elements microscopically, making use of the wave functions of the collective states in terms of particle–hole excitations [2]. This approach provides an important test of our knowledge of the nuclear structure. However, the calculations involved are lenghty and not surprisingly the systematic determination of nuclear deformation parameters by DWBA analyses has mostly relied on the simple macroscopic scheme.

In contrast to the inelastic excitations, particle transfer reactions have only been analysed with microscopic calculations. This is due to the lack of an easily identifiable macroscopic picture pertaining this class of phenomena. While this may remain to be the case for one-particle transfer reactions we would like to advance in this paper a simple prescription for two-particle transfer reactions, based in the analogy between pairing vibrations and the more familiar surface density oscillations (cf. e.g. ref. [3] and references therein).

In a heavy ion collision a nucleus is exposed to the presence of a reservoir of nucleons (i.e. the other partner in the collision). Much in the same way as the relative motion in inelastic processes provides the source of excitation energy we may here consider that the nucleus in question may absorb from this reservoir pairs of nucleons as it sets into motion pairing vibrations. The word "absorb" must, however, be taken in a general sense. While nuclei in their ground state can only take away energy from the relative motion in a process of inelastic excitation, it is in the nature of the phenomenon we discuss here that the nucleus can either pick up nucleon pairs or divest itself from them.

One may a priori expect that conservation of nucleon number requires a careful matching of the transfer

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processes between projectiles and target. We shall nevertheless consider the reaction partner as a passive reservoir and focus our attention in the process in which collective pair vibrations are set into motion in the target. As we shall see later, the implementation of a macroscopic picture requires the relaxation of the number of nucleons as a discrete, conserved quantity.

Assuming the nuclear density to be saturated, the acquisition (or loss) of extra nucleons is achieved by changing the nuclear volume which, in turn, implies a displacement of the nuclear surface. This argument provides a simple way to relate the pair transition density with the radial dependence of the density. In fact, if we use ΔA (i.e. the change in nucleon number) as a plausible candidate for a macroscopic pairing variable, the transition density for pair transfer is given by

$$\Delta\rho^{\mathrm{p}} = (\partial\rho/\partial A)\,\Delta A\,, \tag{1}$$

where

$$\partial\rho/\partial A \simeq (0.4/A^{2/3})\,\partial\rho/\partial r\,. \tag{2}$$

This result represents a deviation from the simple model which considers the pair density to be constant over the nuclear volume. We note, however, that this choice is not essential to the arguments presented here.

Formula (2) paves the way to construct macroscopic pair-transfer cross sections. In fact one can, as a first approximation, use the formalism for inelastic excitations. With the normalization (1) the transition densities for pair and density modes scale in such a way that the corresponding deformation parameters are related by

$$\beta^{\mathrm{p}} = 3A\beta^{\mathrm{v}}\,. \tag{3}$$

Table 1
Reactions analysed with the method described in the text. E_{lab} and Q are the bombarding energy in the laboratory and the reaction Q-value respectively, expressed in MeV. The extracted values of β^{p} and the reference number for the corresponding experimental data are also given.

Reaction	E_{lab}	Q	β^{p}	Reference
^{144}Nd(^{12}C, ^{14}C)^{142}Nd	78	−0.82	5.4	[4]
^{142}Nd(^{18}O, ^{16}O)^{144}Nd	98	1.71	5.3	[5]
^{64}Ni(^{18}O, ^{16}O)^{66}Ni	50	2.90	9.7	[6]
^{64}Ni(^{18}O, ^{16}O)^{66}Ni	57	2.90	9.7	[6]

Examples of angular distributions obtained following this prescription are shown in fig. 1 for the reactions ^{144}Nd(^{12}C, ^{14}C)^{142}Nd, ^{142}Nd(^{18}O, ^{16}O)^{142}Nd and ^{64}Ni(^{18}O, ^{16}O)^{66}Ni. Reaction information and the resulting β^{p} values are given in table 1.

The extraction of the values of β^{p} listed in table 1 relies in the assumption that the data shown in fig. 1 contains information pertinent to the excitation of a target mode. In principle the experimental data does not distinguish between the collective pair excitation

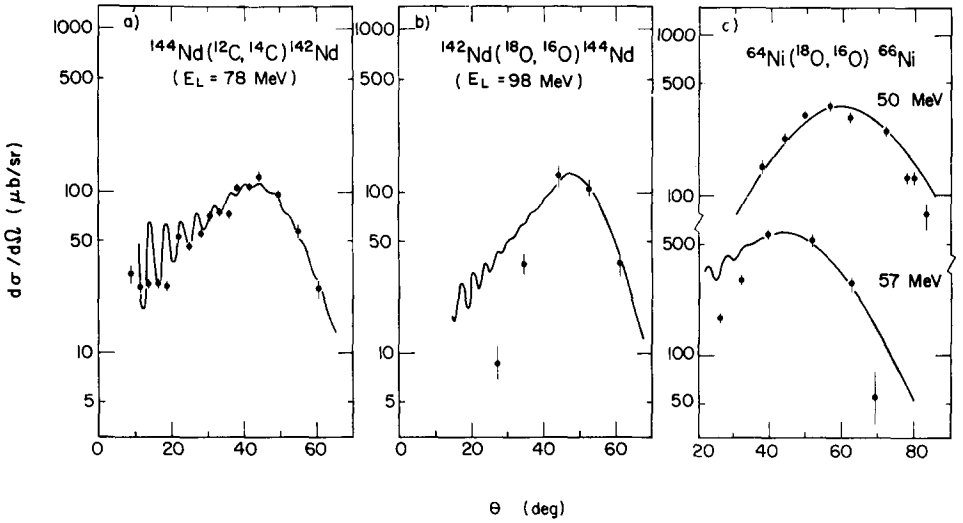

Fig. 1. Differential cross section as a function of scattering angle for the reactions ^{144}Nd(^{12}C, ^{14}C)^{142}Nd, ^{142}Nd(^{18}O, ^{16}O)^{144}Nd and ^{64}Ni(^{18}O, ^{16}O)^{66}Ni. The bombarding energies are indicated in the corresponding frames.

for either partner and, in this sense, it would perhaps be better to consider normal ↔ superfluid systems. Moreover, the ideal data to analyse should be inclusive in the projectile excitations. One can to a certain extent justify the procedure followed above if the pair mode of the projectile is much stiffer than the one in the target. In all cases we have checked that the frequencies of the projectile modes are considerably larger; although this is not a sufficient condition to ignore projectile excitation it gives confidence in the assumed interpretation. Additional support for this ansatz is given by the fact that two reactions involving Nd lead to comparable values of β^{p}.

Associated with the change in the density (1) there will be a modification of the central potential which defines the motion of the nucleons. This provides, as usual, the key to relate the macroscopic picture with single-particle excitations [7]. Exploiting the fact that the range of the nuclear forces is small as compared with the nuclear radius one can relate the variation of the potential with that of the local density and get

$$\delta V = \kappa \Delta A \, F(r) , \tag{4}$$

where $F(r)$ should be interpreted as a local pair field. The introduction of the coupling constant κ allows us to set the normalization of the field F. Following standard practice we choose the deformation scale so that

$$\Delta A = \langle F \rangle , \tag{5}$$

where the expectation value of F is taken in the density deformed by ΔA.

Sustained collective motion in the pair degree of freedom occurs when the change in the potential δV gives rise to excitations which reproduce the change $\delta\rho^{\mathrm{p}}$ as given in (1). This self-consistent requirement is given by

$$\kappa = (0.16 A^{-4/3}) \int (\partial V/\partial r)(\partial \rho/\partial r) r^2 \, \mathrm{d}r . \tag{6}$$

The expression (6) can be easily calculated. Using Fermi functions with standard parameters a monotonically decreasing function of A is obtained. In particular, the coupling constant for ^{208}Pb turns out to be $\kappa \simeq 0.07$ MeV. In this field approximation the microscopic description of the mode can be carried out with an RPA-like formalism in which the operator $\rho^{\mathrm{v}}_{\alpha\beta} = a^{+}_{\alpha} a_{\beta}$ is replaced by

$$\rho^{\mathrm{p}}_{\alpha\beta} = a^{+}_{\alpha} a^{+}_{\beta} + a_{\beta} a_{\alpha} , \tag{7}$$

and the transition density $\delta\rho^{\mathrm{p}}(r)$ is the analogue of the standard transition density

$$\delta\rho^{\mathrm{v}}(r) = \sum_{\mathrm{ph}} [(2j+1)/4\pi]^{1/2} (X_{\mathrm{ph}} + Y_{\mathrm{ph}}) R_{\mathrm{p}}(r) R_{\mathrm{h}}(r) , \tag{8}$$

that is,

$$\delta\rho^{\mathrm{p}}(r) = \sum_{\mathrm{ss}} [(2j+1)/4\pi]^{1/2} (X_{\mathrm{ss}} + Y_{\mathrm{ss}}) R_{\mathrm{s}}(r) R_{\mathrm{s}}(r) , \tag{9}$$

(cf. e.g. ref. [7]). It is noted that eq. (7) defines a generalized density operator that conserves the number of particles only as an average. This is precisely what is required by an oscillation in the number of particles which is described by a macroscopic variable such as ΔA.

The macroscopic picture of pair transfer described here implicitly assumes that the excitation of a pair mode in the target is fed by a superposition of all kind of two-particle, two-hole states in the projectile and vice versa. This, in turn, allows us to introduce the effective one-body field which induces the process. To which degree this picture is supported by the existence of a sum rule for this sort of transitions remains an open question. The extent to which microscopic calculations are able to reproduce the macroscopically extracted values of the deformation parameters β^{p} should also be investigated. Notice, however, that the obtained quantities appear to have the right order of magnitude. For example, calculated transition densities for inelastic excitation [8] and for two particles outside ^{208}Pb [9] scale roughly by a factor of five to ten. This corresponds approximately to the two orders of magnitude that typically separate the values of measured cross sections for inelastic and two-particle transfer processes. Under these conditions $\beta^{\mathrm{p}} \sim 3A \times 10^{-2} \sim$ a few units.

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