TRANSFER REACTION STUDIES WITH SPECTROMETERS*

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The revival of transfer reaction studies benefited from the construction of the new generation large solid angle spectrometers, coupled to large γ arrays. The recent results of γ-particle coincident measurements in ^{40}Ca+^{96}Zr and ^{40}Ar+^{208}Pb reactions demonstrate a strong interplay between single-particle and collective degrees of freedom that is pertinent to the reaction dynamics. The development of collectivity has been followed in odd Ar isotopes populated in the ^{40}Ar+^{208}Pb reaction through the excitation of the $11/2^-$ states, understood as the coupling of single particle degrees of freedom to nuclear vibration quanta. Pair transfer modes is another important degree of freedom which is presently being studied with Prisma in inverse kinematics at energies far below the Coulomb barrier. First results from the ^{96}Zr+^{40}Ca reaction elucidate the role played by nucleon–nucleon correlation.

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1. Introduction

Transfer reactions play an essential role in the study of collision dynamics and nuclear structure. They have an important impact in the understanding of correlations in the nuclear medium, and play a very important role for the study of the evolution from the quasi-elastic to the deep-inelastic and fusion regime [1]. In this case, the constituents of the collision may exchange many nucleons, thus providing information on the contribution of single particle and correlated particle transfers, and on the contribution of surface vibrations (bosons) and their coupling with single particles (fermions).

The recent revival of transfer reaction studies greatly benefited from the construction of the new generation large solid angle spectrometers based on trajectory reconstruction that reached an unprecedented efficiency and selectivity. The coupling of these spectrometers with large γ arrays allowed the identification of individual excited states and their population pattern.

In this paper, we review the main advances in the field done in the last few years. After a brief presentation of the experimental techniques we will discuss the main characteristics of multinucleon transfer reaction. In particular, how a single particle and more complex degrees of freedom act in the transfer process. Some recent results of γ-fragment coincidence measurements and measurement below the Coulomb barrier will be presented, in order to elucidate the role played by nucleon–nucleon correlations in the nuclear medium.

2. Generals on detection techniques

Different techniques have been employed to identify nuclei produced in transfer reactions. Most of these techniques make use of magnetic spectrographs or spectrometers for a complete identification of nuclear charge, mass and energy of final reaction products.

The development of magnetic spectrographs emerged in the past from the need to distinguish excited states populated in light ion transfer reactions. This was achieved by combining magnetic elements of different complexity in order to focus momenta at definite positions on the focal plane. With these instruments, that required corrections for ion optical aberrations, an energy resolution of the order of a few tenths keV could be achieved (Q3D or split pole devices). With heavier ions, more demanding conditions are required in order to keep a good resolution and to have, at the same time, a sufficient detection efficiency. Solutions with emphasis on the complexity of magnetic elements and/or on the detector systems have been adopted, while carefully taking into account the distribution of atomic charge states.

In the demand of measuring weaker and weaker transfer channels the solid angle of spectrometers was increased. To preserve nuclear charge and mass separation, while dealing with heavier and heavier ions, position information becomes crucial. The presently adopted solution for large solid angle spectrometers is the simplified magnetic element configuration and the use of the concept of trajectory reconstruction. The detector system in these spectrometers, besides nuclear charge, energy and timing, provides the necessary position information along the ion path. This idea has been successfully employed in the very large solid angle (100 msr) spectrometers Prisma [2–5], VAMOS [6] and MAGNEX [7].

In these new generation spectrometers, mass and nuclear charge identification has been successfully demonstrated for ions up to $A \sim 100$–130, although energy resolution is presently limited to few hundreds of keV. To reach excited state discrimination for heavy ions the large solid angle magnetic spectrometers have been coupled with large γ arrays (Clara [8], AGATA [9], EXOGAM [10]).

3. Reaction mechanism

The understanding of the reaction mechanism depends strongly on the determination of the absolute cross sections [1, 11]. For grazing collisions, it is expected that a wealth of nuclei are produced in a wide energy and angular range and with cross sections spanning several orders of magnitude. Below are outlined some of the main results concerning the differential and total cross sections, with special emphasis on the new methods which have been developed in order to use the full power of Prisma.

One of the major achievements of the last years, also of significant instrumental value, was the possibility to extract absolute differential cross sections. In order to accomplish this task, one needed to carefully study the response function of the spectrometer, which depends in a complex way on the entrance angles and momenta of the reaction products [12]. An example of the obtained correction factor for the ^{48}Ca ions is depicted in the left panels of Fig. 1 as a function of the scattering angle for several kinetic energy ranges. The ^{48}Ca ions are produced in the ^{48}Ca+^{64}Ni reaction studied at a bombarding energy ~ 2.5 the Coulomb barrier and at quite forward angles [12, 13]. The major corrections of the angular distributions are at the borders of the spectrometer angular acceptance, depending strongly on the kinetic energy of the transported ions. The successful application of the correction method is demonstrated in Fig. 1 (right panels) which shows the angular distributions for the $\pm(1n)$ and $\pm(1p)$ transfer channels.

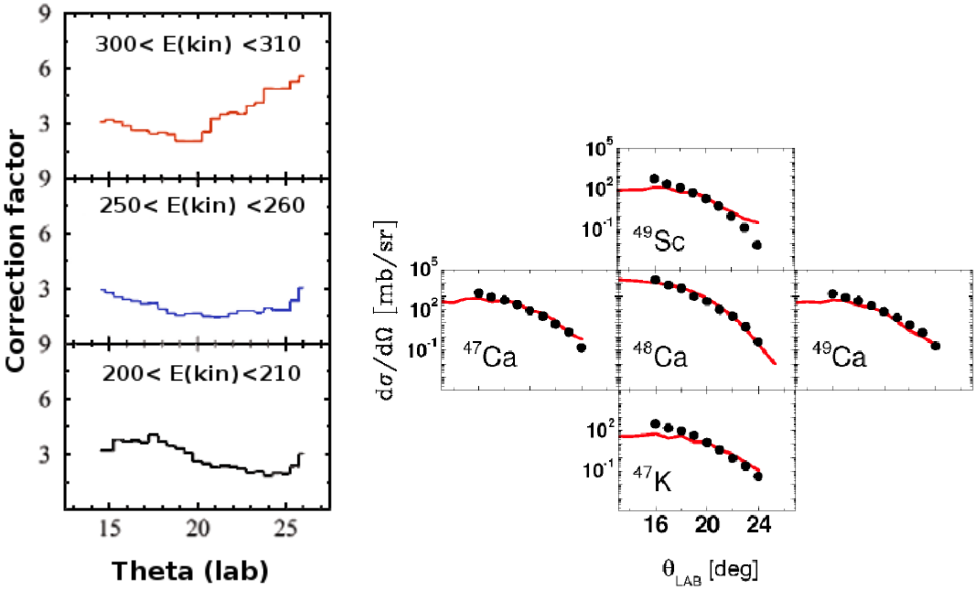

Fig. 1. Left: correction factors for ^{48}Ca as a function of the scattering angle for three different kinetic energy intervals (marked in the panels). Right: angular distributions for the elastic channel, the $\pm(1n)$ channels and the $\pm(1p)$ channels of the ^{48}Ca+^{64}Ni reaction at 6 MeV$/A$. The experimental cross sections have been corrected for the transmission function of Prisma and are shown by symbols while the solid lines give the theoretical predictions from the semiclassical model GRAZING.

Total angle and Q-value integrated cross sections for multineutron and multiproton transfer channels have been investigated with Prisma in various systems close to the Coulomb barrier. As an example, in Fig. 2 we show the total angle and Q-value integrated yields for the pure neutron pick-up channels and the channels involving the one proton stripping in the reaction ^{40}Ca+^{96}Zr [5].

The differential and total cross sections in Figs. 1 (right panels) and 2 are compared with calculations performed with the semiclassical code GRAZING [14]. This model calculates the evolution of the collisions by treating quasi-elastic and deep-inelastic processes on the same footing. It computes how the total reaction cross section is distributed amongst the different reaction channels. The GRAZING model takes into account, besides the relative motion variables, the intrinsic degrees of freedom of projectile and target. These are the surface degrees of freedom and particle transfer. The exchange of many nucleons proceeds via a multi-step mechanism of single nucleons (both, protons and neutrons, via stripping, and pick-up processes).

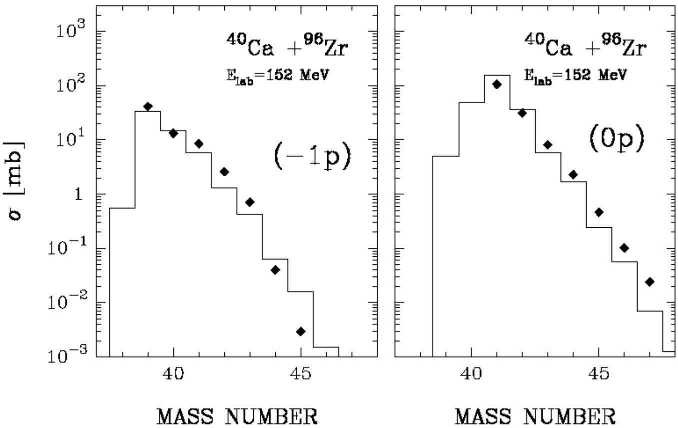

Fig. 2. Total cross sections for pure neutron pick-up (right panel) and one-proton stripping (left panel) channels in the ^{40}Ca+^{96}Zr reaction. The points are the experimental data and the histograms are the GRAZING code calculations (see the text).

Looking at the experimental data of Fig. 2 one finds that the cross sections for the neutron pick-up drop by almost a constant factor for each transferred neutron, as an independent particle mechanism would suggest. The comparison with calculations supports this idea. One can also mention that the pure proton cross sections behave differently, with the population of the $-(2p)$ channel as strong as the $-(1p)$ channel. This suggests the contribution of processes involving the transfer of proton pairs in addition to the successive transfer of single protons [1].

4. Nucleon–nucleon correlations

Heavy-ion transfer reactions are an ideal tool for the study of the residual interaction in nuclei, in particular the components responsible for the couplings between the single particle and phonon degrees of freedom. Via many nucleon transfers one can investigate the component responsible for particle correlations like the pairing interaction.

4.1. Particle vibration couplings

The experimental yields presented in the previous section have been interpreted with the GRAZING model, which, as already outlined, includes the elementary degrees of freedom, surface vibrations, and single particles. It is, in fact, through the excitation of these elementary modes that energy and angular momentum are transferred from the relative motion to these intrinsic degrees of freedom and that mass and charge are exchanged among the two partners of the collision. Here, we concentrate on the one-neutron transfer channel and spectra of ^{41}Ar populated in the ^{40}Ar+^{208}Pb reaction [15]. The fragment-γ coincidences obtained from the coupling of Clara with Prisma allowed us to attribute to each specific reaction product its characteristic γ rays. Figure 3 depicts, as an example, the γ-ray spectra of ^{40}Ar and ^{41}Ar. The spectra comprise transitions partly from particle states and partly from states that involve combinations of single-particle with a collective boson. In ^{40}Ar one notices a very strong population of the 2_1^+ state (we remind that this is the inelastic channel). In ^{41}Ar, the negative parity states, the low lying states with a pronounced single-particle character, for example the $3/2_1^-$ state, are strongly populated. A similar situation was observed in better known ^{39}Ar. In addition, in ^{39}Ar, we observed a strong γ-line from the decay of the $11/2^-$ state. The $11/2^-$ states can be understood as a coupling of a collective boson to single-particle states (*i.e.* $|2^+, (f_{7/2})^1\rangle$) giving a $11/2^-$ stretched configuration.

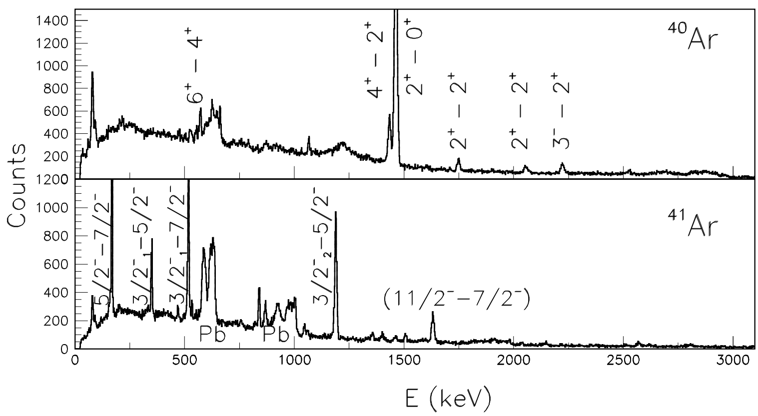

Fig. 3. Doppler corrected γ-ray spectra for ^{40,41}Ar populated in ^{40}Ar+^{208}Pb by detecting the ^{40,41}Ar isotopes in Prisma and the coincident γ rays in Clara. The strongest transitions are marked in the figure.

In ^{41}Ar, besides the population of the known low-lying states which have been recognized in the spectra, the newly observed transitions have been attributed to the $11/2^-$ states (see Fig. 3). A similar situation have been observed in the more neutron rich argon isotopes. The properties of such states are closely connected with the properties of the vibration quanta (see Fig. 4), allowing one to follow the development of collectivity in odd isotopic chain, a phenomenon widely discussed in even–even isotopes. The significant population of states that match a stretched configuration of the valence neutron coupled to the vibration quanta, demonstrates the importance of the excitation of the states whose structure can be explained with the same degrees of freedom which are needed in the reaction model. In fact, the individual state yield distribution in the final reaction products reflects a strong interplay between single-particle and collective degrees of freedom and the reaction dynamics.

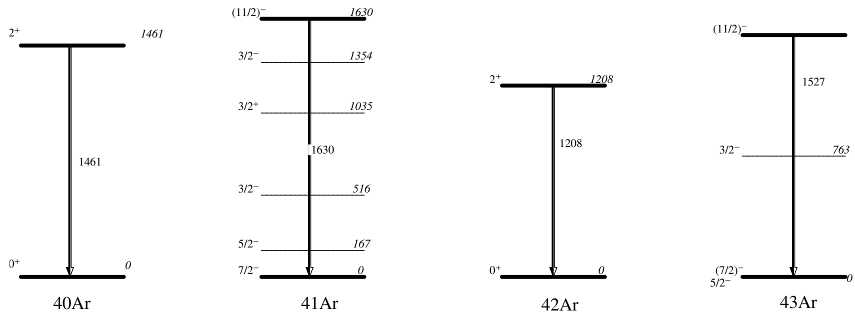

Fig. 4. Experimental energy levels of ^{40,41,42,43}Ar isotopes, plotted as an illustration of the particle-vibration coupling scheme. Only levels relevant to the discussion have been plotted. Arrows indicate the $E2$ transitions.

4.2. Sub-barrier transfer reactions

With heavy ions, as already stressed previously, multiple transfer of nucleons becomes available in the reaction, giving the possibility to study the relative role of single particle and pair transfer modes. Of particular interest is still whether it is possible to reach a situation, where multiple transfer of pairs are dominating the exchange of mass and charge between the interacting nuclei (Josephson effect). The problematics connected with the pair correlations is of current interest in ongoing research with radioactive beams, where, for example, the pairing interaction is expected to be significantly modified in nuclei with extended neutron distributions [16–18].

At energies below the Coulomb barrier, even though the cross sections are much smaller than the ones encountered at higher energies, certain advantages appear when dealing with energies for which the interacting nuclei cannot overcome their mutual Coulomb barrier. In this situation, the two nuclei are kept apart making negligible the formation of compound nuclei and ensuring that the transfer process is a direct one. At the same time, the distortion of the Coulomb elastic waves by the nuclear attraction is very small and may easily be accounted for. The main advantage, however, is that in the calculations of the transfer probabilities one needs only the overlap of the tails of the intrinsic wave functions that are involved in the transfer process.

From the experimental point of view, at energies below the barrier measurements of heavy-ion transfer reactions products present significant technical difficulties. Backscattered ions have low kinetic energies which severely limit their identification, making available data extremely scarce. Also, in the data so far obtained at sub-Coulomb energies, the small solid angle of conventional spectrometers limited the statistical accuracy. We successfully started a new series of measurements by exploiting the large solid angle spectrometer Prisma and by employing inverse kinematics. Detecting ions at very forward angles, we have, at the same time, enough kinetic energy of the outgoing recoils (for energy and therefore mass resolution) and forward focused angular distribution (high efficiency).

Here, we will discuss in more details recent results on sub-barrier transfer measurement for the ^{40}Ca+^{96}Zr system in inverse kinematics [19]. In this system, the projectile (^{96}Zr) and target (^{40}Ca) are closed shell nuclei (or nearly so) for both neutrons and protons thus providing suitable conditions for a comparison with theory. We measured an excitation function of ^{96}Zr+^{40}Ca from the Coulomb barrier to $\simeq$ 25% below [19], measuring the transfer yields down to ~ 15.5 fm of distance of closest approach. Ca-like recoils have been detected by Prisma at $\theta_{\rm lab} = 20°$, corresponding to $\theta_{\rm c.m.} \simeq 140°$.

The transfer probabilities are very well described with an exponential function with a decay length that gets smaller as the number of transferred neutrons increases. This behaviour of the transfer probabilities suggests a simple phenomenological interpretation of the data. By using a simple transfer model based on the exchange of independent particles that predicts for the two particle channel a probability proportional to the square of the single particle probability, one can obtain a nice description for the $+(2n)$ and $+(3n)$ channels with the equations $P_{2n} = 3(P_{1n})^2$ and $P_{3n} = 3(P_{1n})^3$. The factor 3 appearing in the previous expressions represents an enhancement factor whose origin has been addressed by performing microscopic calculations for one and two particle transfer, based on semiclassical theory.

In Fig. 5 results of the measurement are presented together with the calculations for the $+(1n)$ and $+(2n)$ channels. To compute the inclusive one-neutron stripping cross section (full line), we calculated the transfer probability by summing over all possible transitions in projectile and target. One sees how calculations reproduce well the experimental slope as well as the absolute values of the transfer probabilities for the one neutron channel.

For the two particle transfer, we followed closely the formalism which is described in details in Ref. [19]. Here we just mention that the model space contains only two-particle configuration coupled to 0^+ (*i.e.* transfer of a $J = 0^+$ pair). In Fig. 5 with a dotted line we show the calculated probability for the ground-to-ground state transition. Clearly, this transition does not contribute to the total transfer strength in agreement with what was experimentally observed in the Q-value spectra [19, 20]. In the same figure, with a dash line, we show the predicted transfer probability for the transition to the 0^+ state at ~ 5.8 MeV in ^{42}Ca. It is apparent that the contribution of this transition is much larger than the ground state one. At present, we ascribe the enhancement factor of ~ 3 to the fact that the two-nucleon transfer reaction does not populate only 0^+ states but it is much richer, so that more complicated two-particle correlations have to be taken into account. It is being investigated a system involving super-fluid nuclei ^{116}Sn+^{60}Ni [21], and the comparison between data and theory for these two cases, namely nuclei near-closed shells and nuclei of super-fluid character, will significantly improve our understanding of the origin of the enhancement factors.

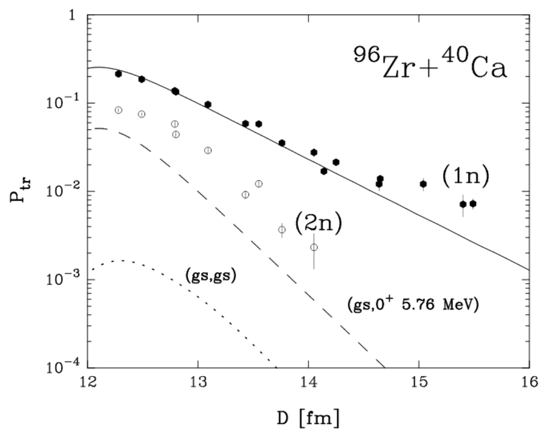

Fig. 5. Theoretical transfer probabilities for one and two particle transfer (lines) in comparison with the experimental data (points). The full line represents the inclusive transfer probability for one neutron transfer, the dotted line the ground–ground state transition for the two-neutron transfer and the dashed line the transition to the first 0^+ excited state at 5.76 MeV in ^{42}Ca (see the text).

5. Summary

We described examples of recent results obtained by employing multinucleon transfer reactions and using the large solid angle spectrometer Prisma and Clara array. We showed how the total and differential cross sections and individual state yield distribution reflect a strong interplay between single particle and collective degrees of freedom. In the comparison between data and theory, we stressed the importance of the elementary degrees of freedom, *i.e.* single particle, phonon and pair modes, in the description of the reaction dynamics. These studies will be of increasing relevance for the ongoing and foreseen experiments with radioactive beams.

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