Quasi-elastic reactions: an interplay of reaction dynamics and nuclear structure

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Abstract.
The revival of transfer reaction studies 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, their population pattern and decay modes via particle-γ coincidences.

In the present paper aspects of fragment-γ coincidence studies measured with the Prisma-Clara set up in 40Ca+96Zr and 40Ar+208Pb are discussed. In particular, we report about states of particle-phonon character, supporting the idea that the relevant degrees of freedom acting in the reaction dynamics define the final yield distributions.

1. Introduction
Transfer reactions play an essential role in the study of the structure of nuclei, in particular with light ions they have been instrumental for the construction of the shell model and they provided important data to establish the properties of particle-particle correlations in the nuclear medium [1]. With heavy ions, the study of transfer reactions was important in the definition of the reaction mechanism [2, 3] that describes the evolution of the reaction from the quasi-elastic to the more complex deep-inelastic and fusion regime [4, 5]. For energies in the vicinity of the Coulomb barrier, transfer of many nucleons constitutes the largest part of the total reaction cross section thus providing the main source for the loss of flux from the elastic channel and for the energy dissipation from the relative motion to the intrinsic excitation.

In the last decade, the renewed interest in transfer reactions has been mainly due to the realization that multinucleon transfer reactions could be used to populate nuclei moderately rich in neutrons. This renewed interest benefited from the construction of the new generation large solid angle spectrometers based on trajectory reconstruction. The coupling of these spectrometers with large γ arrays allowed the identification of γ rays coming from the decay
of the excited states, providing information on the contributions of surface vibrations (bosons), single particles (fermions) and their coupling.

2. Detection techniques for heavy-ion transfer products
In the past, 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 final reaction products in nuclear charge, mass and energy.

The need to distinguish excited states populated in light ion transfer reactions was persuaded by combining magnetic elements of different complexity to focus momenta at definite positions on the focal plane, as for example in Q3D spectrometers. In order to reach an energy resolution of a few tenths keV, the careful corrections for ion optical aberrations were employed.

In order to keep a good resolution and detection efficiency for heavy ions with the large energy dynamic range, solutions with emphasis on the complexity of magnetic elements and/or on the detector systems have been adopted. Dealing with the complex magnetic elements implied that the distribution of atomic charge states of these heavy ions has to be carefully taken into account. To partially overcome this problem, time-of-flight (ToF) spectrometers have been designed with magnetic quadrupole elements which focus ions of different atomic charge states to a relatively small focal plane. All these devices have solid angles in the range $3 - 10$ msr. Beyond these values, it becomes unfeasible to use complex magnetic elements to correct for the ion optical aberrations, thus the presently adopted solution is to simplify the magnetic element configuration and to apply the concept of trajectory reconstruction. This is, at the present, done by using a detector system which, besides nuclear charge, energy and timing, provides the necessary position information along the ion path. The reconstruction of the ion trajectory inside magnetic elements in order to identify the transfer reaction products, has been successfully employed in the very large solid angle (80 msr) spectrometer Prisma [6].

2.1. The Prisma-Clara set-up
Prisma consists of a magnetic quadrupole singlet, placed at 50 cm from the target, and a magnetic dipole. Its main characteristics are a large dispersion and a large momentum acceptance, well adapted for the detection of the kinematics of grazing collisions, where a wealth of nuclei are produced in a wide energy and angular range and with cross sections spanning several orders of magnitude. A position-sensitive micro-channel plate (MCP) detector [7] is placed at the entrance of the spectrometer, providing a start signal for time-of-flight measurements and position signals. Ions pass through the optical elements of the spectrometer and enter a focal plane [8] which is made of a parallel plate of multiwire type (MWPPAC), providing timing and position signals with resolutions similar to the MCP ones. Behind the MWPPAC is an array of a transverse field multiparametric ionization chambers (IC), providing nuclear charge ($\Delta E$) and total energy ($E$). The IC due to its sub-division can be optimized for the best $Z$ and energy resolutions and to stop at once the ions that differ by more than 20% in kinetic energy.

The $\gamma$-ray array Clara [9] consists of 24 HP-Ge clover-type detectors placed as a hemisphere close to the target and opposite to Prisma. The total photopeak efficiency of Clara is of the order of 3% for $E_\gamma = 1.33$ MeV. Typical $\gamma$-ray energy resolutions obtained after Doppler correction are 0.6% to 0.9% over the whole velocity distribution of the fragments detected in Prisma.

In Prisma, the mass identification of the reaction products is obtained via an event-by-event reconstruction of the ion trajectory inside the magnetic elements [10]. The identification of nuclear charge $Z$ is obtained through the measurement of energy loss $E$ in the IC, which also provides the total energy $E$. The charge resolution of Prisma is illustrated in Fig. 1, where we plotted the two-dimensional spectrum of the total energy (IC) vs. total range (the combination
Figure 1. The two-dimensional spectrum of the total energy (IC) vs. total range (the combination of different $\Delta E$ sections of IC) for the $^{40}\text{Ca}+^{96}\text{Zr}$ reaction measured at $E_{\text{lab}} = 152$ MeV and at the grazing angle.

Figure 2. Left panels: Mass spectra for argon, potassium, and calcium isotopes populated in the $^{40}\text{Ca}+^{96}\text{Zr}$ reaction. The inset in the bottom panel displays the neutron pick-up channels on a logarithmic scale. Right panels: Mass spectra for potassium, argon, and chlorine isotopes populated in the $^{40}\text{Ar}+^{208}\text{Pb}$ reaction. (Note the different scaling factors in each panel.)

of different $\Delta E$ sections of IC) for the $^{40}\text{Ca}+^{96}\text{Zr}$ reaction measured at $E_{\text{lab}} = 152$ MeV and at the grazing angle.

The reconstructed mass spectra for calcium (pure neutron pick-up channels), potassium (one-proton stripping channels), and argon (two-proton stripping channels) isotopes of the $^{40}\text{Ca}+^{96}\text{Zr}$ (left panels) and for chlorine (one-proton pick-up channels), argon (neutron transfer channels) and potassium (one-proton stripping channels) isotopes of the $^{40}\text{Ar}+^{208}\text{Pb}$ (right panels) reactions are shown in Fig. 2.

The fragment-$\gamma$ coincidence obtained from the coupling of Clara with Prisma allows us to attribute to each specific reaction product its characteristic $\gamma$ rays. Since the $\gamma$ rays are emitted in flight it is mandatory to perform Doppler correction. This is done from the knowledge of the
Figure 3. The γ spectrum of $^{42}$Ca, the two-neutron pick-up channel of the $^{40}$Ca+$^{96}$Zr reaction.

Figure 4. 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 calculation performed with the code GRAZING.

trajectory reconstructed in Prisma, which provides the velocity vector of the emitting nuclei. The γ spectrum plotted in Fig. 3 demonstrates the reached resolution with this procedure.

3. Phenomenology of MNT

The presently achieved quality of data and of the agreement between theory and measurement is demonstrated in Fig. 4. The figure shows a comparison of the experimental integrated cross sections for one-proton stripping and pure neutron pick-up channels of the $^{40}$Ca+$^{96}$Zr reaction as a function of the number of transferred nucleons with semi-classical calculations [11, 12]. The figure reflects some of the main characteristics of quasi-elastic processes, which we discuss here in more details.

The dependence of the cross sections on the number of transferred neutrons is very similar to the one observed in other studied systems [13, 14]. Multinucleon transfer reactions are governed by optimum Q-value consideration, and using stable ions they dominantly populate neutron pick-up and proton stripping channels. The charge and mass distribution of produced nuclei indicates the dominance of a direct mechanism in the population of different fragments. The neutron pick-up drops by almost a constant factor for each transferred neutron as an independent
mechanism would suggest. The pure proton transfer 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 correlated nucleons in addition to the successive transfer. For the massive proton transfer channels the isotopic distributions drift toward lower masses, a clear indication that these large proton transfer channels are affected by the secondary processes, as evaporation. The calculated cross sections have been obtained by using the semiclassical model GRAZING [11, 12]. This model calculates the evolution of the reaction by taking into account, besides the relative motion variables, the intrinsic degrees of freedom of projectile and target. These are the surface modes and the single-nucleon transfer channels. The multinucleon transfer channels are described via a multistep mechanism. The relative motion of the system is calculated in a nuclear plus Coulomb field. The excitation of the intrinsic degrees of freedom is obtained by employing the well-known form factors for the collective surface vibrations and the one-particle transfer channels. The model takes into account in a simple way the effect of neutron evaporation. The good agreement between experiment and theory gives us confidence on the correct treatment of the quasi-elastic regime.

4. The character of states populated in transfer reactions

The experimental yields, shown in the previous section, have been interpreted with a model that explicitly treats the internal degrees of freedom of the two ions in terms of elementary modes, surface vibration and single particles. Following this description heavy-ion collisions provide a suitable tool for the studies of the particle-vibration coupling scheme. Here we concentrate on the one-neutron transfer channels and spectra of $^{96}$Zr populated in the $^{40}$Ca+$^{96}$Zr, and of $^{41}$Ar populated in the $^{40}$Ar+$^{208}$Pb reactions. In both cases, the spectra of the nuclei populated in the reaction can be mostly explained by single-particle or single-hole states and states that involve combinations of a single particle or hole with a collective boson.

A well studied laboratory for the weak particle-phonon coupling is the vicinity of the $^{208}$Pb nucleus, since its first excited state is the collective 3$^-$ state [15]. The collectivity of 3$^-$ is not dominated by a few particle-hole components but derives from the cooperative action of many configurations. The $^{96}$Zr and $^{40}$Ar nuclei present a more complicated situation. The low-energy spectrum of $^{96}$Zr is dominated by a 2$^+$ state at 1.75 MeV and by the 3$^-$ at 1.90 MeV. This last state is very collective $[B(E3;3^- \rightarrow 0^+ = 51 \text{ W.u.}]$ and decays via an E1 transition to the 2$^+$ and via an E3 transition to the ground state. The ground state of $^{95}$Zr is well described by a neutron hole in the $d_{5/2}$ orbital. By coupling this hole state with the 3$^-$ one expects a sextet of states (1/2$^-$,3/2$^-$, ..., 11/2$^-$) at an energy close to the one of the 3$^-$. Similarly, by coupling the same hole state to the first 2$^+$ one expects a quintet (1/2$^+$, 3/2$^+$, ..., 9/2$^+$) at an energy close to one of the 2$^+$ state in $^{96}$Zr. This situation is illustrated in Fig. 5. The reaction mechanism does not populate the components of the two multiplets uniformly but favors the stretched configurations 11/2$^-$ and 9/2$^+$ since the transfer probability has its maximum at the largest angular momentum transfer. From the adopted levels of $^{95}$Zr, we recognized transitions 11/2$^- \rightarrow (9/2^+, 9/2^+) \rightarrow (7/2^+)$, and (7/2$^+ \rightarrow 5/2_{2s}$, as well as the new transition at 2022 keV which we naturally interpret as the E3 decay of 11/2$^-$ to the ground state. The intensity of this transition, relative to the E1, is very similar to the one observed in $^{96}$Zr, thus reinforcing our interpretation that the 11/2$^-$ is a member of a boson-hole $[3^-, (d_{5/2})^{-1}]$ multiplet [10].

A very similar situation seems to emerge in the Ar isotopic chain populated via neutron pick-up channels in the $^{40}$Ar+$^{208}$Pb reaction. Looking at the spectra of the even argon isotopes we notice the strong population of the yrast states, and in particular of the 2$^+$ state. As already mentioned, in the reaction model the excitation and transfer processes are mediated by the well known single-particle form factors for the fermion degrees of freedom and by the collective form factors, for the vibrational modes. These states act as core excitation in the odd isotopes when a neutron is added. In fact, in the odd Ar isotopes, $^{39,41,43}$Ar, besides the transition between the
lowest lying levels, a strong population of the $11/2^-$ states has been observed. The $11/2^-$ state can be understood as a coupling of collective boson to single-particle states (i.e. $|2^+, (f_{7/2})^1>$ giving an $11/2^-$ stretched configuration). The energies of these $11/2^-$ states were compared with the $sd – pf$ large-scale-shell-model calculations, and the coupling schemes are illustrated in Fig. 6.

This significant population of $11/2^-$ states, reached via neutron transfer, demonstrates the importance of excitation of the states whose structure can be explained with the same degrees of freedom which are needed in the reaction model, i.e. coupling of the valence neutron to the vibration quanta.

5. Summary
We have presented some of the recent results of reaction mechanism studies carried out at LNL, Legnaro laboratory. Multi-nucleon transfer reactions have been studied with the large solid angle magnetic spectrometer Prisma, where ions identification is achieved by reconstructing
event-by-event the trajectory of the ions in the magnetic elements. Experimental yields have
been compared with the semi-classical model GRAZING that includes surface vibrations and
single particle transfer modes and taking into account the effect of neutron evaporation. By
coupling the Prisma spectrometer with the high resolution Clara $\gamma$-array it has been shown
how the transfer process populates reaction products in regions of angular momentum and
excitation energy quite different from fusion-evaporation processes. This has been exploited to
gain information on states that can be interpreted along the particle-vibration coupling scheme.

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