Quasi-elastic reactions: a survey on recent results

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Abstract.
Binary reactions at energies close to the Coulomb barrier received recently a significant boost thanks to the advent of the large solid angle magnetic spectrometer PRISMA coupled to the $\gamma$ array CLARA. In the present paper different aspects of the recent results of nuclear structure and reaction dynamics will be presented, focusing more closely on the reaction mechanism.

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. With heavy ions, the transfer studies were further extended. The two colliding partners can exchange a large number of nucleons, thus enabling to probe the pair density in the nuclear medium. From the reaction mechanism point of view, the study of multinucleon transfer reactions provides an insight about which degrees of freedom have to be included in any model in order to describe the evolution of the heavy-ion reaction from the quasi-elastic to the deep inelastic regimes and to fusion [1].

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, with a large gain in overall efficiency while still keeping a good identification of reaction products. The coupling of these spectrometers with large $\gamma$ arrays allowed the identification of $\gamma$ rays coming from the decay of weak transfer channels associated with the population of nuclei moderately far from stability.

In this work a discussion on transfer yields, nucleon-nucleon correlation and the connection between multinucleon transfer reactions and other competing reaction channels is presented. An emphasis will be given to the discussion on the recent results of $\gamma$-particle coincidence measurements with PRISMA+CLARA. [2, 3, 4].
Figure 1. Angle and $Q$-value integrated cross sections for pure proton stripping and pure neutron pick-up channels of the $^{40}$Ca+$^{208}$Pb reaction at $E_{\text{lab}}=235$ MeV as a function of transferred nucleons. The points and histograms are experimental and theoretical (CWKB) values, respectively. The dashed lines are the results of CWKB calculations using sequential transfer only, while the solid lines also include pair-transfer modes.

2. Nucleon-nucleon correlations

The presently achieved quality of data and of the agreement between theory and measurement is demonstrated in figure 1. The figure shows a comparison of the experimental angle and $Q$-value integrated cross sections for pure proton stripping and pure neutron pick-up channels of the $^{40}$Ca+$^{208}$Pb reaction as a function of the number of transferred nucleons [5] with semiclassical calculations [6, 7]. A clear identification of the transfer products is obtained up to the pick-up of $\sim$six neutrons and the stripping of $\sim$ six protons. The bombarding energy is close to the Coulomb barrier and the yield, measured at the grazing angle, reflects some of the main characteristics of quasi-elastic processes. The charge and mass distribution of produced nuclei indicates the dominance of a direct mechanism in the population of different fragments. The plot shows that the neutron pick-up drop 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 proton pairs in addition to the successive transfer of single protons. One observes that the pair-transfer mode gives an essential contribution to the proton transfer channels (left panel), while its
contribution is almost negligible for the neutron channels (right panel).

Nuclear structure calculations have shown that the pairing interaction has the same strength for both neutrons and protons [8]. Since the one-neutron transfer cross section is almost one order of magnitude larger than the one-proton transfer, the contribution of a pair-transfer mode is masked, in the neutron sector, by the successive mechanism. However, it is important to point out that the microscopic treatment of pair modes is still a theoretical challenge.

Multinucleon transfer reactions are governed by optimum Q-value consideration, and using stable ions they dominantly populate neutron pick-up and proton stripping channels. In order to study proton-neutron correlation one has to use systems where the population of the \( np \) channels is allowed by the \( Q \)-value. In particular it is important to study the \(+ (np)\) channel which can be populated via a direct mechanism, at variance with the \( -(np) \) channel which is of complex nature since it can be strongly affected by neutron evaporation mechanism (see next section). Such a goal can be achieved by using neutron rich beams, thus, we have performed a measurement of \(^{40}\text{Ar} + ^{208}\text{Pb}\) by using the PIAVE+ALPI LNL accelerator complex with an \(^{40}\text{Ar}\) beam at 250 MeV. The \( M - Z \) spectra is plotted in figure 2. The figure clearly shows that the proton pick-up and neutron stripping channels start to be populated. The experimental yields have been compared with GRAZING calculation [9, 10]. The yields have been normalized to the computed \(+1n\) channel and the same normalization constant has been kept for other neutron and proton pick-up and stripping channels. The dependence of the cross sections on the number of neutron pick-up and proton stripping channels turns out to be very similar to the one observed in other studied systems [5, 11]. A good agreement between data and theory is obtained for the transfer of pure neutrons and for channels
involving the stripping of one proton (−1p). Noteworthy is the fact that the shape of the mass yield for the (−1p) case is well reproduced, also, on the neutron pick-up side. The proton pick-up channel (+1p) is well reproduced, while these preliminary results indicate that some additional degrees of freedom have to be considered for the (+1p + xn) channels.

Important complementary information can be achieved by looking at the population pattern of individual states, as the effect of the pairing interaction is to redistribute the transfer flux in a way to enhance states of specific structure. The spectra of the neighboring nuclei populated in the reaction comprise partly single particle or hole states and partly states that involve combinations of these states with collective boson. The transfer processes studied here are governed by well known properties of single particle and collective states, and through the excitation of these elementary modes the energy and angular momentum are transferred from the relative motion to the intrinsic degrees of freedom.

For these reasons, the character of the states populated in neutron transfer reactions have been studied in more details. In even Ar isotopes the strongest transitions between the yrast states have been observed. Besides them, the non-yrast feeding of the 2+ and 0+ states is also present. In the odd Ar isotopes, besides the transition between the lowest lying levels, a strong population of the 11/2− states have been observed. Recent shell model calculations [12, 13] stress the importance of the coupling of collective boson to single-particle states (i.e. 2+ to \( f_{7/2} \), giving an 11/2− stretched configuration). Multinucleon transfer reactions, in comparison with light ion induced transfer reactions, have larger probabilities for the population of stretched configurations, as the transfer probability has its maximum at the largest angular momentum transfer. It is important to notice that the de-excitation spectra may quite differ from the excitation ones. The quadrupole and octupole matrix elements generally play a major role in the excitation process, while the de-excitation may be dominated by very small components in the wave function. Thus, the structure of the studied nucleus together with the production mechanism strongly affects the observed spectra. Analysis of all populated nuclei is in progress.

The measured total cross sections shown in figures 1 and 2 refer to the secondary reaction products [11, 14]. The primary yield can be in fact considerably altered by evaporation processes due to large kinetic energy loss components.

3. Evaporation

Making use of the \( \gamma \)-particle coincidence technique and exploiting the binary character of transfer reactions a direct evidence of particle evaporation processes can be outlined. With magnetic spectrometers, by detecting a specific Z and A the velocity vector of the undetected partner can be evaluated and applied for the Doppler correction of its corresponding \( \gamma \) rays. In figure 3 we show as an example the \( \gamma \) spectra for \(^{40}\text{Ar} \) (detected) and its associated binary partner in the \(^{40}\text{Ca}+^{96}\text{Zr} \) reaction [4]. One clearly
Figure 3. $\gamma$ spectra for the $-2p + 2n$ channel in the reaction $^{40}$Ca+$^{96}$Zr Doppler corrected for the heavy (top two frames) and light fragments (bottom frame). To have a better identification of the different $\gamma$ lines for the heavy fragment we used an expanded energy scale.

sees that in the Mo spectra are present not only the $\gamma$ rays belonging to the primary partner but also those of the nuclei produced after evaporation takes place. The yield associated with these neutron evaporation channels becomes progressively more marked for massive transfer channels. For instance in the $-4p$ channel the primary binary partner has negligible yield. A direct signature of how evaporation modifies the final yield distribution by correlating projectile-like and target-like fragment isotopic yields was outlined in [15] via $\gamma-\gamma$ coincidences. These two experimental techniques give comparable yield for neutron evaporation.

4. Summary

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 semi-classical models that include 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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