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Multinucleon transfer reactions: a mini-review of recent advances

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Multinucleon transfer reactions, characterized by the exchange of many nucleons at energies in the vicinity of the Coulomb barrier, have been extensively used in the last decades to understand the production of neutron-rich nuclei, as well as to study their structure. In this Mini Review, recent results related to the production mechanism of heavy neutron-rich nuclei obtained with stable and radioactive beams will be discussed together with the results concerning the proton transfer channels. Additionally, newest results from a series of experiments carried out to study nucleon-nucleon correlations for closed-shell and superfluid systems employing the large solid angle magnetic spectrometer PRISMA will be summarized.

KEYWORDS

low-energy heavy-ion reactions, multinucleon transfer reactions, neutron-rich nuclei, nucleon-nucleon correlations, magnetic spectrometers

Introduction

Multinucleon transfer (MNT) reactions between heavy ions at energies around the Coulomb barrier are characterized by the exchange of many nucleons between the target and the projectile with a population of relatively low excitation energy and of relatively high spins [1]. They have been extensively used in the last decades to populate moderately neutron-rich mid-mass nuclei with cross sections large enough to study their structure [1–3]. Specifically, valuable information on single-particle states, collective excitations, and their coupling [4–13], are offered by one-nucleon transfer channels, while transfer of nucleon pairs yields information on nucleon-nucleon correlations [14–17]. As more nucleons are getting transferred, it is possible to populate nuclei farther from the stability and to study the evolution of reaction from quasi-elastic to deep-inelastic regime.

In the quasi-elastic regime, the mass and charge distributions of transfer products are governed by optimum *Q*-value considerations and transfer form factors [1]. As a result, the neutron pick-up and the proton stripping channels of the projectile-like fragments are dominantly populated when lighter stable projectiles are used on heavy targets [1]. The transfer flux changes already with the use of more neutron-rich stable projectiles in which case proton pick-up channels open up [18]. With neutron-rich projectiles, the trend should turn and the proton pick-up and neutron stripping channels should dominate, leading to the population of neutron-rich heavy fragments [18–23]. This pathway is very interesting for nuclear structure investigations, for example for the understanding of the evolution of magic numbers far from stability [24–26], and for nuclear astrophysics investigations, where heavy-element synthesis in the *r*-process is particularly intriguing [27, 28].

MNT as a method to produce heavy neutron-rich nuclei

Multinucleon transfer reactions were predicted to be a competitive method for the production of heavy neutron-rich nuclei in the pivotal work of Dasso and collaborators [19]. More recently, it has been predicted that the neutron-rich region around the magic number $N = 126$ can be approached by using stable beams at energies around the Coulomb barrier in deep-inelastic collisions (DIC) [29]. These predictions were experimentally studied in the last years with careful selection of the colliding systems which are suitable to populate proton pick-up channels at energies around the Coulomb barrier. Many of these studies are based on the powerful combination of selective large solid angle magnetic spectrometers such as PRISMA [30–32] in Legnaro National Laboratories in Italy and efficient γ-ray detectors [2, 33, 34]. Even so, the study of proton pick-up channels is still in its beginnings and reaction products have been identified in atomic number, mass and Q-value for only a few systems.

In this section we will present our selection of some of the measurements concerning the production of heavy neutron-rich nuclei. Measurements have been performed for the ^{144}Sm+^{88}Sr [35] and ^{48}Ca+^{124}Sn [36] systems to study nucleon correlation effects and complex (i.e., pair/cluster) degrees of freedom in the transfer process. On the other hand, indirect measurements of cross sections based on the knowledge of the level schemes, using characteristic γ rays, were performed for few heavy systems [37–39].

Recently a high resolution study of the absolute production cross sections of neutron-rich nuclei in the ^{136}Xe+^{198}Pt system [22] gained a lot of attention. Measurement performed with the VAMOS++ magnetic spectrometer [40], to identify light reaction partner, and EXOGAM γ-array [41] showed that the main contribution to the formation of heavy neutron-rich nuclei such as Hg and Os arise in collisions with a small excitation energies where the particle, mainly neutron, evaporation is minimized. Experimental results have been compared with the GRAZING code [42–44] that calculates the evolution of the reaction by taking into account, besides the relative motion, the intrinsic degrees of freedom of projectile and target. These are the isoscalar 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 model, to calculate the isotopic distributions of the produced fragments, takes into account, in a simple way, the effect of neutron evaporation. The code has been successfully applied in the description of MNT reactions and in general gives good description of the neutron and few proton transfer channels. However, it was observed that for more proton stripping and pick-up channels the measured distributions peak at lower and higher mass values, respectively, as compared to the GRAZING calculations that take into account only impact parameters close to the grazing angle. The difference from the calculation indicates the presence of large energy losses and significant influence of neutron evaporation.

The total cross sections of proton pick-up channels were further measured for the ^{40}Ar+^{208}Pb system where the focus was on obtaining the total transfer strength [18]. This was achieved by measuring the angular distribution for the light reaction partners over large range of angles spanning three angular and magnetic field settings of the PRISMA spectrometer and by taking into account the spectrometer's response function [45, 46]. This allowed to study the evolution of quasi-elastic to DIC. Disentangling between different contributions is challenging from both experimental and theoretical side since they are substantially mixed and may strongly overlap. However, insight was gained by identifying reaction products in mass and charge, and by measuring total kinetic energy loss (TKEL) and angular distributions over wide range of angles, as well as by comparing these experimental observables with theoretical calculations. As can be seen from Figure 1A, the deviations between experimental data and GRAZING calculations are more pronounced for the proton (especially pick-up) channels, when neutron transfer channels are involved. The contributions from DIC were extracted and identified to be significant. This is especially relevant at energies substantially higher than the Coulomb barrier, where DIC, as well as secondary effects, become more and more relevant.

Secondary processes, such as neutron evaporation and fission, especially from ^{238}U, can significantly modify the final yield distribution of heavy primary nuclei mainly towards the lighter isotopes. It is important to quantitatively understand their relevance and to study the best experimental conditions for the largest survival probability of the neutron-rich nuclei populated in MNT reactions. The cross section studies for proton pick-up channels have been performed with the ^{238}U target for the ^{64}Ni+^{238}U [20] and ^{136}Xe+^{238}U [21] systems. In the latter case, studies of the influence of secondary processes on MNT were carried out by measuring the time-of-flight differences between different coincident reaction products. In this way it was possible to distinguish between transfer, fission and elastically scattered particles which helped to determine the fraction of MNT reaction products compared to fission. Neutron evaporation channels were clearly identified thanks to AGATA [33, 34] and it was observed that as more neutrons are transferred to the target nucleus, more evaporated neutrons are detected. This strongly affects the final yield distribution of both binary partners and limits the production of very neutron-rich nuclei. It is important to note that proton pick-up channels have higher survival probability than stripping channels, leading to more neutron-rich final reaction products.

Although information on the heavy partner can be obtained indirectly by detecting the coincident γ rays produced by the reaction products [21, 31], significant progress has been made

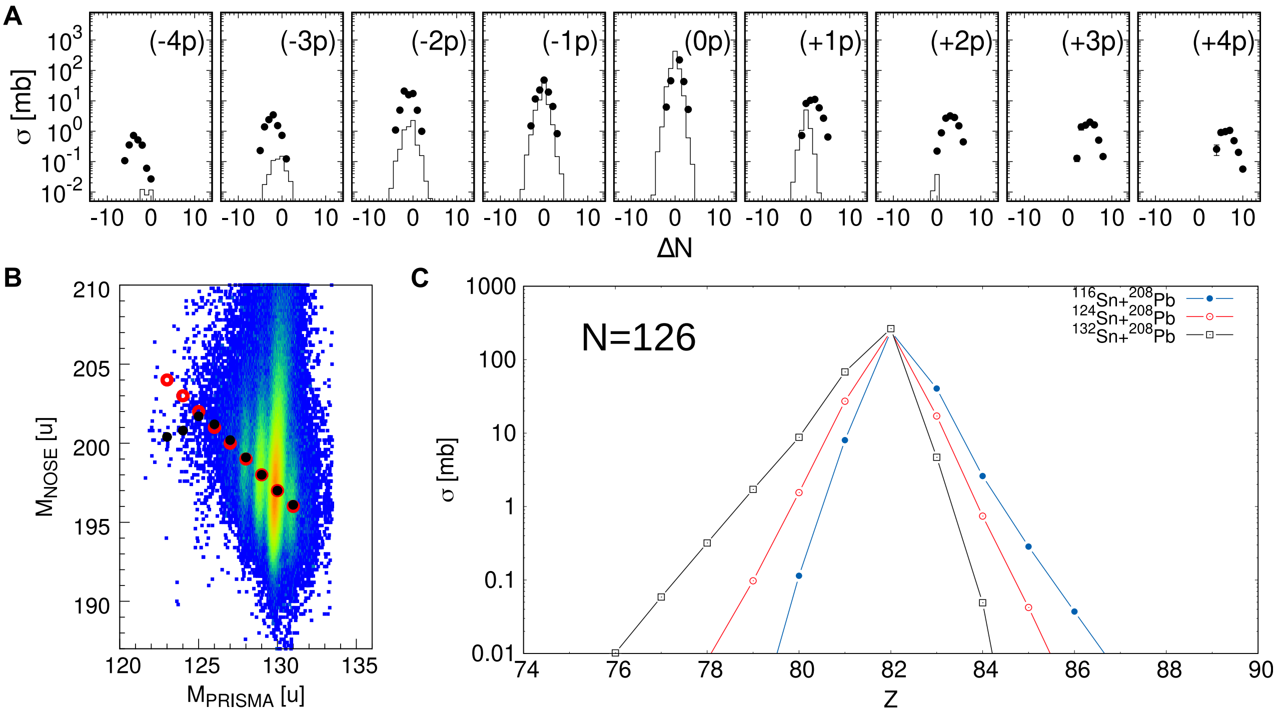

FIGURE 1
(A) Total experimental cross section for the ^{40}Ar+^{208}Pb system, at beam energy E_{lab} = 6.4 MeV/A (points), and the GRAZING calculations with neutron evaporation (solid line), figure is adapted with permission from [18] **(B)** Mass-mass correlation matrix of Te isotopes detected in PRISMA and the heavy partner detected in coincidence with NOSE for the ^{197}Au+^{130}Te system. The red circles indicate the centroids of the correlated masses of the primary neutron transfer channels, the black dots indicate the experimental centroids as derived from the fits of their projections [47] **(C)** GRAZING calculations for the ^{116}Sn (stable), ^{124}Sn (the most neutron-rich stable) and ^{132}Sn (neutron-rich) projectiles on the ^{208}Pb target at the beam energy 20% above the Coulomb barrier.

with a simultaneous detection of light and heavy transfer products in the ^{197}Au + ^{130}Te system [47]. The high-resolution kinematic coincidence measurement has been performed with PRISMA coupled to a second arm detector NOSE [48]. This helped, via a mass-mass correlation, to understand and quantify the production process also for the heavy partner of the reaction. To better understand the effect of secondary processes, the de-excitation process of the produced heavy fragments has been simulated with a Monte Carlo method, starting from the binary character of the reaction, to understand their final mass distribution. These results, shown in Figure 1B, indicated that the primary fragments acquire significant excitation energy and allowed to extract information on the average number of evaporated neutrons for each channel associated with the Te isotopes. The focus was on pure neutron transfer channels and the extracted total cross sections well agree with calculations performed with the GRAZING code down to several neutron transfers. However, a better knowledge of the underlying mechanisms is essential considering that the main excitation energy of the recoils can be rather high.

A definite dominance of the proton pick-up and neutron stripping channels in the distribution of the transfer flux of the light partner, leading to the proton stripping and neutron pick-up in the heavy partner of the reaction, is predicted to occur by using neutron-rich projectiles, in most cases, five to seven neutrons away from the last stable isotope [19]. Results of the GRAZING calculations for the ^{116}Sn (stable), ^{124}Sn (the most neutron-rich stable) and ^{132}Sn (neutron-rich) projectiles on the ^{208}Pb target at the beam energy 20% above the Coulomb barrier are shown in Figure 1C for the reaction products with $N = 126$. The shift toward more neutron-rich reaction products with $Z < 82$ is clearly seen, and calculations predict an order of magnitude larger cross section when using neutron-rich rare-isotope beam. Experimentally, first step in this direction is the absolute cross sections determination for neutron transfer channels populated in the ^{94}Rb+^{208}Pb reaction [23]. Cross sections have been extracted by directly identifying the lead isotopes with the high-efficiency MINIBALL γ-ray array [49]. The observed sizable cross sections in the neutron-rich mass region are in fair agreement with the GRAZING calculations. This confirms the predicted change of population pattern and is of great importance for future studies of nuclear structure, in particular near the N = 126 shell closure, with MNT reactions and radioactive beams. These studies will be considerably improved with the particle detection systems able to identify reaction products in A and Z and by measuring the cross sections to the ground states which can be substantial.

Experimental results confirm that MNT reactions are a suitable tool to produce exotic neutron-rich nuclei [22, 23]. In comparison with fragmentation and fission, the production cross sections of nuclei along N = 126, Z < 82 with MNT reactions appear to be much larger, especially for lower atomic numbers [22]. However, one should take into account the larger target thicknesses and experimental efficiencies in the fragmentation reactions [50, 51]. Even so, it is still of great interest to continue these studies to see if MNT reactions and radioactive beams offer access to neutron-rich region south of doubly magic Pb nucleus, that is out of reach for other methods.

Finally, different theoretical models are becoming available partially thanks to the use of super-computers. These developments in reaction theory must consider the adequate treatment of the reaction dynamics, realistic structure models and proper effective interactions. Some of the newer approaches include the improved quantum molecular dynamics (ImQMD) model [52–56] and time-dependent Hartree-Fock (TDHF) theory [57–66]. Nowadays it is possible to take into account quantal fluctuations and correlations going beyond the TDFH approach [67–70]. Therefore, precise measurements of experimental observables, especially absolute cross sections, angular and TKEL distributions, and disentangling between different effects that contribute to the reaction cross section, can be used to validate different theoretical models in order to optimize the population of the exotic nuclei of interest. This comparison of different models and experimental data should give better insight in the MNT reaction mechanism and help to develop our understanding of low-energy heavy-ion reactions.

Nucleon-nucleon correlations

Two-nucleon transfer reactions are among the best tools to investigate nucleon-nucleon correlations which are induced by the pairing interaction [71–74]. With heavy ions, the reaction dynamics is complex and only recently microscopic calculations achieved a good agreement with the experimental data [14, 15, 17]. This was possible because measurements were performed in a wide energy range from near to well below the Coulomb barrier where the interacting nuclei are only slightly influenced by the nuclear potential and Q values are restricted to a few MeV for the open transfer channels. These conditions diminish the complexity of coupled channel calculations. The data were represented via the transfer probability (P_{tr}) (defined as a ratio of the transfer yield over the quasielastic one) plotted as a function of the distance of closest approach (D) for the Coulomb trajectory. The use of the PRISMA spectrometer and inverse kinematics allowed one to measure P_{tr} down to very large values of D, sufficiently far from the nuclear absorption region, with good ion identification, and information could be extracted on the nucleon-nucleon correlations.

The total transfer probability for one-neutron transfer channel was obtained by summing over all possible transitions that can be constructed from the single-particle states in the projectile and target for the ^{96}Zr+^{40}Ca [14] and ^{116}Sn+^{60}Ni [15, 16] systems and the results are shown in Figure 2. These calculations well reproduce the experimental slope and the absolute values of the transfer probabilities. For the two-nucleon transfer, the transfer probability was calculated for the 0^+ states. The ground-to-ground state transition alone could not reproduce experimental result for the ^{96}Zr+^{40}Ca system as can be seen in Figure 2A. In fact, the predicted transfer probability for the transition to the excited 0^+ state in ^{42}Ca is much larger, in agreement with the measured Q-value spectra. In conclusion, it was found that the two-neutron transfer probability is enhanced as compared to a simple expectation of independent particle transfer process, i.e., the square of one-neutron transfer probability. The coupled-channels calculations performed for this system also suggested a significant effect of the couplings to the collective excited states around the Coulomb barrier [75]. The TDHF + BCS formalism was also applied for this type of reactions [76, 77].

The experimental transfer probabilities for ^{116}Sn+^{60}Ni shown in Figure 2B have been well reproduced, for the first time with heavy ions for the two-neutron transfer channel, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon pairing correlations, microscopically calculated optical potentials and successive transfer processes [15]. In particular, the employed microscopic theory reproduces very well the data by considering solely the ground-to-ground state transition. This was possible because in this system (superfluid nuclei) the ground-to-ground state Q values for one- and two-neutron transfer are very close to optimum (~0 MeV). The validity of this approach was confirmed by performing a fragment-γ coincidence experiment for the same system [16], employing the PRISMA spectrometer coupled to the AGATA demonstrator [33]. It was possible to conclude that a large fraction of the total strength of the (2n) channel, more than 76%, goes to the ground state.

Recent theoretical calculations interpreted ^{116}Sn+^{60}Ni data as a manifestation of a nuclear (alternating current) Josephson effect with Cooper pairs tunneling between the superfluid nuclei [17, 78, 79]. The coherence length was determined thanks to the large range of D over which transfer probability was measured. A transfer of a neutron pair between interacting binary partners generates a dipole oscillation whose frequency is

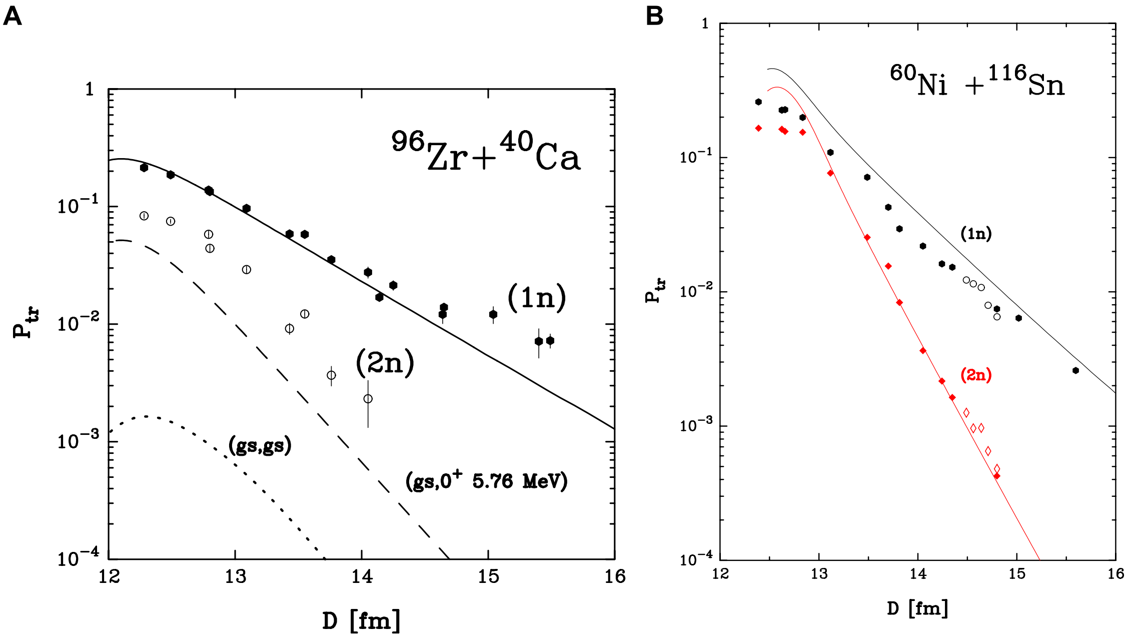

FIGURE 2

Theoretical transfer probabilities P_{tr} for the one- and two-neutron transfer (lines) in comparison with the experimental data (symbols) for the ^{96}Zr+^{40}Ca **(A)** and ^{116}Sn+^{60}Ni **(B)** systems plotted as a function of the distance of closest approach D **(A)** The full line represents the inclusive transfer probability for one-neutron transfer, the dotted line the ground-to-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 [14] **(B)** Open symbols correspond to the results from the angular distribution in direct kinematics while solid symbols refer to the excitation function measurement performed in inverse kinematics [16].

determined by the ground state Q-value [17]. The short interaction time of scattering, ~ 10^{-21} sec, leads to three to four back-and-forth transfer cycles that can produce observable consequences. A γ-ray strength distribution centered at ~4 MeV is predicted. These predictions can be experimentally tested thanks to the powerful coupling of PRISMA and AGATA.

More work is needed in order to better understand the role of a transfer of a pair by confronting theory with experiments involving different nuclei. In this respect, valuable insight will be given by the ^{206}Pb+^{118}Sn system [80, 81] recently measured with PRISMA. This is the heaviest (asymmetric) semi-magic system with closed proton and open neutron shells, and well Q-value matched for neutron transfers. Important questions that can be answered in this case are whether and to what extent the effect of neutron-neutron correlations is modified in the presence of high Coulomb fields and do DIC and multistep processes significantly modify the transfer strength near the ground states. The transfer strength of the ground-to-ground state transitions may significantly change in the collisions of very heavy ions thanks to the population of final states with high excitation energies and large angular momenta. Additionally, it would be interesting to see whether any enhancement factors can be observed in the collisions of two doubly magic nuclei.

Nucleon-nucleon correlations studies should be extended to even less understood role of neutron-proton and proton-proton correlations [82]. The study of neutron-proton correlations has been done with nuclei along the $N = Z$ line to investigate the isovector and isoscalar components (for some of the recent results see Refs. [83–88]), while the data for the proton-proton correlations are more scarce [82]. It would be of great interest to extend these studies to transfer reactions with heavy ions even if the transfer probabilities for protons are generally smaller at the same D and more difficulties are encountered than in the case of neutrons from both experimental and theoretical point of view. These measurements can be advanced by the coupling of a spectrometer and an efficient γ-array which could provide important additional information for both one and two-proton transfer.

Finally, the advent of new radioactive beam facilities [89–92] should provide access to the nuclei with an extended neutron distribution and should allow the possibility to study the density dependence of the pairing force. Particularly interesting is the (closed shell) region of ^{132}Sn and beyond to look at the modification of the properties of pair transfers. Some work has been done with the halo nuclei, as for instance with ^{11}Li induced reactions providing evidence of phonon mediated pairing [93, 94]. The comparison of data concerning the dynamic effects of pairing correlations with different microscopic theories (for instance [15, 17, 95]), as well as cross comparison between reactions performed with stable and radioactive beams, will provide valuable insight into the role of the pair (neutron and/or proton) transfer in the MNT reactions.

Author contributions

TM wrote the manuscript on behalf of the PRISMA collaboration.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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