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**T Mijatović[1], S Szilner[1], L Corradi[2], F Galtarossa[2], D Montanari[3], G Pollarolo[4], P Čolović[1], G Colucci[3], E Fioretto[2], A Goasduff[3], D Jelavić Malenica[1], T Marchi[2], G Montagnoli[3], N Soić[1], F Scarlassara[3], A M Stefanini[2] and J J Valiente-Dobón[2]**

[1] Rudjer Bošković Institute, Zagreb, Croatia
[2] Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Legnaro, Legnaro, Italy
[3] Università di Padova, and Istituto Nazionale di Fisica Nucleare, Padova, Italy
[4] Università di Torino, and Istituto Nazionale di Fisica Nucleare, Torino, Italy

E-mail: `tea.mijatovic@irb.hr`

**Abstract.** We present some of the recent experimental results in heavy-ion transfer reactions obtained with the large solid angle magnetic spectrometer PRISMA at energies close to the Coulomb barrier. We focus on a series of experiments that have been carried out to study the nucleon-nucleon correlations for closed shell and superfluid systems. They are discussed together with the newest results concerning the proton transfer channels above and below the Coulomb barrier. The second set of the experiments was performed to study the production mechanism of heavy neutron-rich nuclei and the related effects of secondary processes.

## 1. Introduction

Particle-particle correlations induced by the pairing interaction are essential in defining the properties of finite quantum many-body systems in their ground and neighboring states. These structure properties may significantly influence the evolution of the collision of two nuclei. An ideal tool to study the dynamical aspects of pairing correlations are the two-particle transfer processes, among which the quasi-elastic reactions are very promising.

In studies of pair correlations in heavy-ion collisions few experiments have been performed in the past [1]. The possible signature of the correlations was proposed to be an enhancement of the cross section that, experimentally, may be estimated from the comparison of the measured two-particle transfer probability (or cross section) with the prediction of models using uncorrelated states. Unfortunately the main part of the existing studies involved inclusive cross sections at energies higher than the Coulomb barrier and at angles forward of the grazing angle where the reaction mechanism is more complex. Therefore, it is still important to understand how the transfer of a pair of nucleons and correlations affect the quasielastic processes.

## 2. Multinucleon transfer reactions above the barrier

In the quasi-elastic regime the mass and charge distributions of transfer products are governed by the optimum $Q$-value considerations and transfer form factors [2]. For nuclei close to the stability line, these optimum $Q$-value arguments favor the neutron pickup and the proton stripping

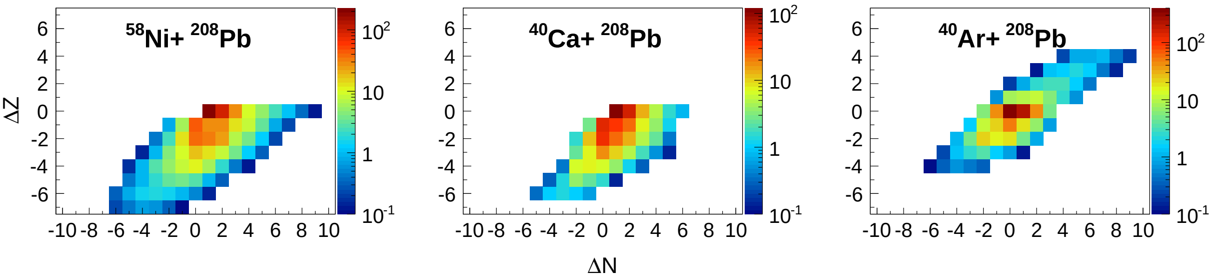


**Figure 1.** Angle and energy integrated total cross section for $^{40}$Ar, $^{40}$Ca, and $^{58}$Ni projectiles on the $^{208}$Pb target, at energies $E_{lab}$ = 6.4, 6.2, and 6 MeV/A, respectively. The cross section values of the elastic (+inelastic) channel have been scaled down by a factor 100 to better display the behavior of the transfer channels [3].

channels (pickup and stripping are referring to the lighter reaction fragment). This is illustrated in Fig. 1 [3] that shows the measured cross sections for the stable open shell $^{58}$Ni+$^{208}$Pb [4] and closed shell $^{40}$Ca+$^{208}$Pb [5] systems where the reaction mechanism strongly favors the proton stripping and neutron pickup channels. This is the reason why multinucleon transfer reactions have been used as a competitive tool for the production of neutron-rich nuclei in the vicinity of the light partner [6]- [12]. It is also evident how the transfer flux changes with the use of the neutron-rich (stable) projectiles like $^{40}$Ar and how proton pickup channels open up.

The data for all three systems were compared with calculations performed with the semi-classical code GRAZING [13]. In all systems GRAZING well describes the one nucleon transfer channels. Other pure neutron transfer channels are also well reproduced, particularly neutron pickup channels. Deviations between experimental data and calculations are more marked for the channels involving the transfer of many protons. This fact has been discussed in previous publications where experimental cross sections were compared with different semi-classical models in order to see if the addition of new modes, in particular the transfer of a pair of nucleons (both neutrons and protons), may be justified [5]. The inclusion of these pair-transfer modes may be essential, however, the contribution from deep-inelastic processes may also be substantial and needs to be considered.

Other theoretical approaches for the multinucleon transfer reactions are rapidly developing and were quite successfully compared with some of the mentioned data, for example the Time-Dependent Hartree-Fock [14] or the Langevin type approach [15].

## 3. Nucleon-nucleon correlations

Recently, several systems have been measured with the large solid angle magnetic spectrometer PRISMA [16, 17] for the study of nucleon-nucleon correlations both in direct and inverse kinematics over a wide energy range with cross sections for one- and two-nucleon transfer spanning several orders of magnitude. This type of experiments is best represented with transfer probabilities, defined as the ratio of the transfer yield over the quasi-elastic one, plotted as a function of the distance of closest approach for a Coulomb trajectory.

Making use of inverse kinematics, target recoils have been detected in multinucleon transfer reactions for the $^{96}$Zr+$^{40}$Ca (closed-shell nuclei) [18] and $^{116}$Sn+$^{60}$Ni (super-fluid nuclei) [19] systems. An excitation function has been obtained from the Coulomb barrier to 20-25% below. At energies well below the Coulomb barrier the contribution of different channels and mechanism is much lower. 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, since one needs to take into account only a few

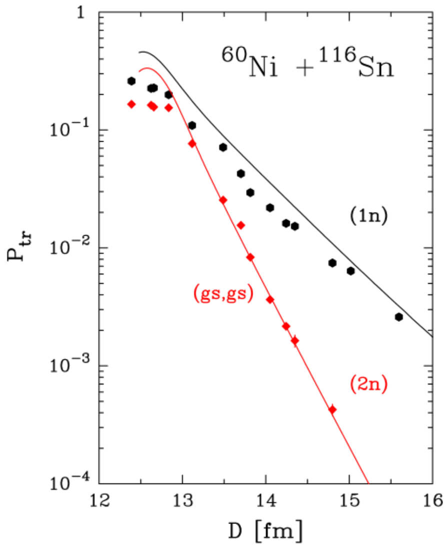


**Figure 2.** Experimental (points) and microscopically calculated (lines) transfer probabilities for the one- and two-neutron pickup in the $^{116}$Sn+$^{60}$Ni system plotted as a function of the distance of closest approach $D$ [19].

populated states, and information may be extracted on the nucleon-nucleon correlations.

Figure 2 shows the experimental transfer probabilities for the one- and two-neutron transfer channels in the well $Q$-value matched system, $^{116}$Sn+$^{60}$Ni, compared with microscopic calculations. For the two-neutron transfer channel, the calculations incorporate nucleon-nucleon correlations, essential for the population pattern of the single particle levels around the Fermi energy, and dynamical and structure properties of both nuclei, where all known structure information of the entrance and exit channel nuclei was included [19]. The employed microscopic theory reproduces very well the experimental data in all energy ranges, in particular the transfer probability is very well reproduced, in magnitude and slope, by considering solely the ground-ground state transition. The validity of this approach was confirmed by performing a fragment-$\gamma$ coincidence experiment for the same system [20], employing the PRISMA spectrometer coupled to the Advanced Gamma Tracking Array (AGATA) demonstrator [21]. We have extracted the strengths for the observed transitions, and we were able to conclude that the transitions to the excited states are a small fraction of the total strength of the (2n) channel, not more than 24%.

Important questions are whether and to what extent the effect of neutron-neutron correlations in the evolution of the reaction is modified in the presence of high Coulomb fields and do deep inelastic components and multistep processes significantly modify the transfer strength near the ground states. To answer them, the measurement was performed in inverse kinematics by using the $^{206}$Pb beam. The chosen $^{206}$Pb+$^{118}$Sn system is the heaviest (asymmetric) semi-magic system with closed proton and open neutron shells, and well matched in $Q$-value for neutron transfers. The analysis is underway and results will be crucial for completing the picture about neutron-neutron correlations.

### *3.1. Proton channels*
Proton transfer channels are more difficult to measure below the barrier since their cross sections drop off more rapidly than those of neutron transfer channels. Therefore, the proton transfer processes in a heavy-ion collisions are much less understood than those of neutrons, since large modification in the trajectories of the entrance and exit channels are involved due to

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the modification of the Coulomb field.

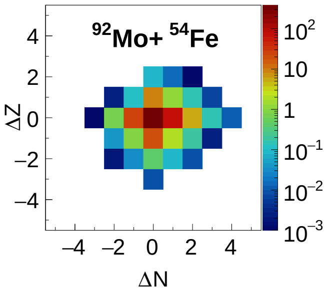


**Figure 3.** GRAZING calculated cross section for the target-like products in the $^{92}$Mo+$^{54}$Fe collision at 370 MeV.

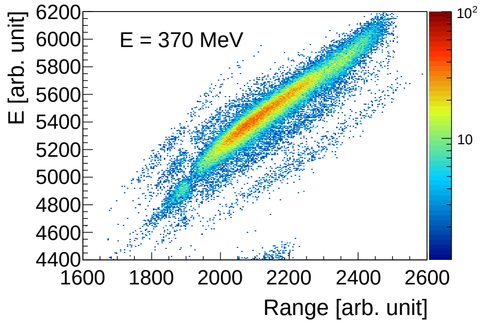


**Figure 4.** Range-energy matrix for $^{92}$Mo+$^{54}$Fe at 370 MeV shows clear identification of different proton channels produced in the reaction.

We made an experiment dedicated to the study of proton transfer channels around and below the barrier. We chose the $^{92}$Mo+$^{54}$Fe system involving proton-rich nuclei, where both neutron and proton pickup and stripping channels on $^{54}$Fe become available, following the optimum $Q$-value considerations. This can be seen in Fig. 3, that shows the GRAZING calculations for this system. The experimental data, the range-energy matrix for the highest measured energy close to the Coulomb barrier, are shown in Fig. 4. One can experimentally identify different proton transfer channels, and quite symmetric distribution was obtained.

A clear identification of different proton transfer channels has been achieved even below the barrier. The (±2p) channels are quite strong, as well as alpha channels that are much stronger than predicted. The alpha transfer channels become even stronger below the barrier, and we found that the yield of the "alpha" transfer channels are similar to those of the pure two proton transfer channels. However, one has to keep in mind that the cross sections are derived by integrating the whole TKEL distributions.

Even if it is expected that at the energies below the Coulomb barrier the energy distribution (TKEL) will become narrower and will concentrate in the single state, the fragment-$\gamma$ coincidences are crucial to determine which state is dominantly populated, and thus to define the correct phase space used in the calculations. Therefore, we measured, for the same system, high energy resolution fragment-$\gamma$ coincidences by using the $^{54}$Fe beam at the bombarding energy close to the Coulomb barrier. The probabilities obtained via excitation function and angular distribution should be very similar provided that the large energy loss components correspond to a small fraction of the cross sections. To measure electromagnetic transitions we used the new array of six 2"x2" $LaBr_3$ scintillators. The measured strength distributions will be crucial to understand to what extent the strong population of the (2p) and "(alpha)" channels can be due to simple reaction mechanism effects or whether nucleon-nucleon correlations play a role.

## 4. Production of heavy neutron-rich nuclei

A definite dominance of the proton pickup and neutron stripping channels in the distribution of the transfer flux is predicted to occur with an additional increase of the neutron excess in the projectile [22]. Such a situation leads to the population of neutron-rich nuclei in the corresponding heavy partner [23]. However, the primary yield can be influenced by secondary processes that generally shift the mass distributions toward lower values. It is still crucial to better understand the production mechanism for neutron-rich nuclei in the $A$=200 mass region and the effects of secondary processes on the final yields of fragments.

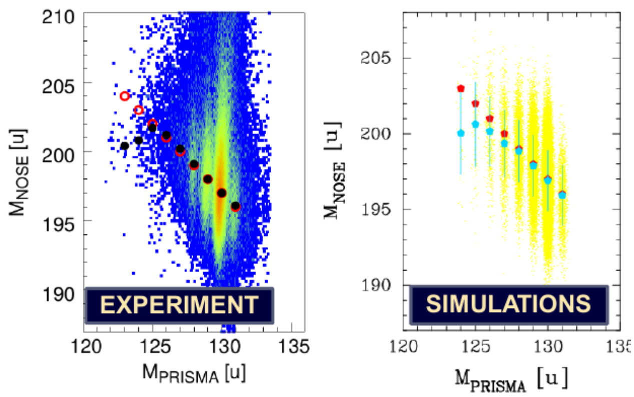


**Figure 5.** Left: Mass-mass correlation matrix of Te isotopes detected in PRISMA and the heavy partner detected in coincidence with NOSE. The red circles indicate the centroids of the correlated masses of the primary neutron transfer channels, the black dots indicate the experimental centroids as derived from the fits of their projections. Right: Simulated mass-mass correlation matrix. The points are the centroids of the primary (red) and actual (blue/light gray) Au isotope distributions. The blue/light gray bars represent the standard deviations [24].

In order to better understand and quantify the production process also for the heavy partner of the reaction, we performed a high resolution kinematic coincidence experiment with a simultaneous detection of light and heavy transfer products in the $^{197}$Au+$^{130}$Te system in the inverse kinematics [24]. We chose the neutron-rich $^{130}$Te target to populate neutron transfer channels leading primarily to neutron-rich Au isotopes. We exploited the performance of the PRISMA spectrometer to identify isotopes in the tellurium region, while the coincident Au-like partners were detected with the second time-of-flight system NOSE [25].

A coincidence with a high resolution spectrometer allows one to reconstruct a mass-mass correlation matrix and to infer about the behaviour of the heavy partner. This is nicely demonstrated in Fig. 5 left, where the reconstructed mass of the Au-like ions is correlated with that of the mass distribution of the Te-like ions detected in PRISMA. The high resolution mass identification of the light fragment allows to separate the mass distribution of the heavy partner in well-defined bands. The black dots indicate the centroids of the projections of each band, showing how they slightly bend toward lower masses in comparison to those expected for the corresponding primary neutron transfer channels (red circles). The simulations, shown in Fig. 5 right, incorporate an evaporation of neutrons taking into account the experimental TKEL distributions (to compute evaporation), the cross sections measured in PRISMA and the experimental resolution. These results indicate that the primary fragments acquire significant excitation energy so that evaporation becomes relevant in defining the final yields. Furthermore, it was possible to extract information on the average number of evaporated neutrons for each channel associated with the Te isotopes.

The studies of the optimal conditions in which multinucleon transfer reactions can be used as a mechanism to populate neutron-rich nuclei are essential since the effect of the evaporation depends strongly on the bombarding energy, as well as the projectile and target combination. Recently an experiment was performed at ISOLDE-CERN with the $^{94}$Rb projectile and the $^{208}$Pb target with one aim being to understand the degrees of freedom which influence the evolution of the reaction and the cross sections that can be reached for the production of the neutron-rich nuclei in the vicinity of $N$=126 region [26].

## 5. Summary

Transfer reactions with heavy ions are a powerful tool to investigate reaction mechanism and structure properties of nuclei. Transfer of several nucleons at the same time gives the possibility to study the relative role of a transfer of one particle and pair of nucleons. This was studied in the sub-barrier transfer reaction measurements where the nuclei interact at large distances and the information about correlations are extracted when experimental absolute cross sections are compared with a microscopic theory which beside correlations includes the coupling between relative motion (reaction) and intrinsic motion (structure).

Multinucleon transfer reactions are also a very good tool for the production of heavy neutron-rich nuclei. With the use of neutron-rich projectiles new perspectives open up. However, we still need more experimental studies of the best selection of mass asymmetry and collision energy for the largest survival probabilities of heavy partners. These studies are relevant for the future investigations with radioactive beams, especially considering the SPES project [27].

## Acknowledgments

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## References

[1] Wu C Y, von Oertzen W, Cline D, Guidry M W 1990 *Annu. Rev. Nucl. Part. Sci.* **40** 285-326
[2] Corradi L, Pollarolo G and Szilner S 2009 *J. Phys. G: Nucl. Part. Phys.* **36** 113101
[3] Mijatović T, *et al.* 2016 *Phys. Rev.* C **94** 064616
[4] Corradi L, *et al.* 2002 *Phys. Rev.* C **66** 024606
[5] Szilner S *et al.* 2005 *Phys. Rev.* C **71** 044610
[6] Lunardi S *et al.* 2007 *Phys. Rev.* C **76** 034303
[7] Valiente-Dobón J J *et al.* 2009 *Phys. Rev. Lett.* **102** 242502
[8] Szilner S *et al.* 2011 *Phys. Rev.* C **84** 014325
[9] Szilner S *et al.* 2013 *Phys. Rev.* C **87** 054322
[10] Chapman R *et al.* 2016 *Phys. Rev.* C **93** 044318
[11] Vogt A *et al.* 2016 *Phys. Rev.* C **93** 054325
[12] Litzinger J *et al.* 2018 *Phys. Rev.* C **97** 044323
[13] A. Winther, Nucl. Phys. A **572**, 191(1994); A. Winther, Nucl. Phys. A **594**, 203 (1995); program GRAZING http://www.to.infn.it/∼nanni/grazing
[14] Sekizawa K 2017 *Phys. Rev.* C **96** 014615
[15] Saiko V and Karpov A 2019 arXiv 1907.09352
[16] Szilner S, *et al.* 2007 *Phys. Rev.* C **74** 024604
[17] Corradi L, *et al.* 2013 *Nucl. Instr. and Meth.* B **317** 743
[18] Corradi L, *et al.* 2011 *Phys. Rev.* C **84** 034603
[19] Montanari D, *et al.* 2014 *Phys. Rev. Lett.* **113** 052601
[20] Montanari D, *et al.* 2016 *Phys. Rev.* C **93** 054623
[21] Akkoyun S, *et al.* 2011 *Nucl. Instr. and Meth.* A **668** pp 26-58
[22] Dasso C H, Pollarolo G and Winther A 1994 *Phys. Rev. Lett.* **73** 1907
[23] Watanabe Y X *et al.* 2015 *Phys. Rev. Lett.* **115** 172503
[24] Galtarossa F, *et al.* 2018 *Phys. Rev.* C **97** 054606
[25] Fioretto E, *et al.* 2018 *Nucl. Instr. and Meth.* A **899** 73
[26] Čolović P, *et al.* 2019 *Basic Concepts in Nuclear Physics: Theory, Experiments and Applications. RABIDA 2018. Springer Proceedings in Physics* A **225**
[27] https://web.infn.it/spes/