Recent results with the magnetic spectrometer PRISMA

E. Fioretto[1], *L. Corradi*[1], *S. Szilner*[2], *D. Montanari*[3], *C. Michelagnoli*[3], *T. Mijatović*[2], *G. Montagnoli*[3], *F. Scarlassara*[3], *A.M. Stefanini*[1], *C.A. Ur*[3], *G. Pollarolo*[4], *N. Soić*[2] *and the PRISMA and CLARA collaborations*

[1]INFN - Laboratori Nazionali di Legnaro, Viale dell'Università 2, Legnaro (PD), I-35020, Italy
[2]Ruđer Bošković Institute, Bijenička 54, Zagreb, HR-10001, Croatia
[3]Dipartimento di Fisica dell'Università di Padova and INFN, Via Marzolo 8, Padova, I-35131, Italy
[4]Dipartimento di Fisica Teorica dell'Università di Torino and INFN, Via P. Giuria 1, Torino, I-10125, Italy

Abstract
Large acceptance magnetic spectrometers have come into operation in the last decade, such as PRISMA installed at Laboratori Nazionali di Legnaro, and have given a further boost to the renewed interest for multinucleon transfer reactions. The large solid angles of these devices and the high resolving powers of their detection systems allowed to investigate the transfer process around and well below the Coulomb barrier and to perform nuclear structure studies in several mass regions of the nuclide chart when coupled with large γ-ray arrays such as CLARA or the AGATA Demonstrator. Recent results of reaction dynamics and nuclear structure obtained with PRISMA and PRISMA-CLARA as well as a new ancillary detector for the spectrometer will be presented in this paper.

1 Introduction

The renewed interest in the last decade for multinucleon transfer reactions, mainly due to the realization that this process could be used to populate nuclei moderately rich in neutrons, benefited from the construction of the new generation tracking spectrometers, based on the trajectory reconstruction, and the use of the state-of-art large area particle detectors.

PRISMA [1, 2, 3] is the large acceptance magnetic spectrometer designed to be used with heavy-ion beams accelerated at energies up to E = 10*A* MeV by means of the Tandem/PIAVE-ALPI accelerator complex of Laboratori Nazionali di Legnaro. It can operate as a standalone device or coupled to large γ-ray arrays such as the CLARA [4] set-up until March 2008 or the AGATA Demonstrator [5] until the end of December 2011. Its coupling with the CLARA array allowed to make in-beam γ-spectroscopy of moderately neutron-rich nuclei populated by multinucleon transfer reactions through the identification of individual excited states and their population pattern. The experimental campaign of the PRISMA-CLARA set-up started in 2004 and has been completed at the end of March 2008 making use of about 50% of the total beam-time available at the Tandem/PIAVE-ALPI accelerator complex of LNL. Experiments performed with PRISMA and PRISMA-CLARA were mainly addressed to obtain information on the nucleon-nucleon correlation and the connection between multinucleon transfer process and other competing reaction channels, on the shell evolution and the onset of new regions of deformation (collectivity, critical point symmetries) in medium-mass moderately neutron-rich nuclei.

Selected results obtained with the PRISMA and PRISMA-CLARA set-ups in sub-barrier transfer measurements and in odd argon isotopes populated by using the multinucleon transfer process are presented in this contribution. Moreover, the status of an ancillary detector which is being developed for PRISMA in order to perform kinematical coincidence measurements is also reported.

2 Sub-barrier transfer measurements

Multinucleon transfer in heavy ion reactions is a mechanism ranging from the quasi-elastic regime (i.e. few nucleon transfer and low total kinetic energy loss (TKEL)) to the deep-inelastic collisions (i.e. many nucleon transfer and large TKEL) which takes into account the largest fraction of the total reaction cross section at energies close to the Coulomb barrier [6]. In the sub-barrier region nuclei enter into contact through the tail of their density distributions and nucleon transfer processes take place between levels close to the Fermi surfaces of the donor and acceptor. At such large distances between the centres of the interacting nuclei the reaction mechanism conditions are much simplified compared to those near the strong absorption radius. Nuclei are only slightly influenced by the nuclear potential and follow almost pure Coulomb trajectories. Excitation energies are restricted to few MeV and uncertainties in calculations associated with optical potentials can be minimized. These peculiar conditions should in principle allow to extract more quantitative information on the mechanism of multiple transfer processes, for example on the relative contribution of single particle and more complex degrees of freedom which include nucleon-nucleon correlations. However, available data for heavy ion transfer reactions in the sub-barrier region are extremely scarce or almost not existing due to the significant experimental difficulties of this kind of measurements (such as the strongly backward peaked angular distributions, the low kinetic energy for the backscattered projectile like fragments and the low cross sections). A suitable way to overcome these limitations is to make use of inverse kinematics detecting the lighter targetlike fragments with magnetic spectrometers at very forward angles [7, 8]. The coming into operation of large solid angle spectrometers has renewed the interest for the study of the transfer process in the sub-barrier region where a high efficiency is required.

In this framework we measured with the spectrometer PRISMA the excitation functions for the neutron transfer channels populated in the inverse kinematics ^{96}Zr+^{40}Ca reaction [9] from the Coulomb barrier (330 MeV) to ~ 25% below (275 MeV). Projectile and target are closed or near-closed shell nuclei for both neutrons and protons, thus representing a good reference for a quantitative comparison with theoretical calculations. This experimental and theoretical environment provides very suitable conditions for a proper study of the mechanism of multiple transfer processes. The ^{96}Zr beam was accelerated by the Tandem-ALPI accelerator complex of LNL onto a 50 μg/cm^2 $^{40}CaF_2$ target supported on a 15 μg/cm^2 C backing. Mass spectra of the targetlike fragments, measured with magnetic spectrometer PRISMA placed at 20°, have evidenced the population of more than four neutron pick-up channels at energies close to the Coulomb barrier while at sub-barrier energies only one or at most two neutron transfers survive. Making use of semiclassical conditions, one can extract the transfer probability P_{tr} as a function of the distance of closest approach D, with P_{tr} defined as the ratio of transfer cross sections to the Rutherford one. This representation is significant only if semiclassical conditions are fulfilled and one deals with (almost) pure Coulomb trajectories. The case studied here well fulfils these requirements, with the further advantage that the Q-value distributions at the measured sub-barrier energies are quite narrow and corresponding to few MeV of excitation energy. At large ion-ion separation the radial behaviour of the form factor is governed by the exponential form of the bound-state wave function and the transfer probability is approximated by:

$$P_{tr}(\theta) \cong e^{-2\alpha D(\theta)} \tag{1}$$

where the parameter α is related to the binding energy E_b of the transferred nucleon, $\alpha = (2mE_b)^{1/2}/\hbar$, and $D(\theta)$ is the distance of closest approach. The excitation functions of transfer processes as a function of the distance of closest approach D are thus represented (in a semi-logarithmic plot) by straight lines with a slope -α. Such behaviour is independent of the way in which transfer proceeds, as a successive process or as a simultaneous transfer. Contradictory results have been obtained in previous experiments around the Coulomb barrier, where slopes smaller than predicted were found [8], and at lower energies where no anomaly in the slope behaviour has been clearly identified [10]. Figure 1 displays the transfer probabilities extracted from the yields of the +1n (full circles), +2n

(empty circles) and +3*n* (full triangles) transfer channels as a function of the distance of closest approach *D*, together with the solid lines which are the results of the fitting procedure. Data for the +4*n* channel (empty triangles) are available only at the highest energies, therefore a reliable fit could not be performed. The extracted experimental slopes agree well with those expected by the binding energies. Given the correct behaviour of P_{tr} and keeping in mind the simplified assumptions mentioned before, we can make a phenomenological analysis which compares the probabilities for transfer channels with those expected from an independent particle transfer mechanism. It turns out that $P_{2n} = 3(P_{1n})^2$ and $P_{3n} = 3(P_{1n})^3$.

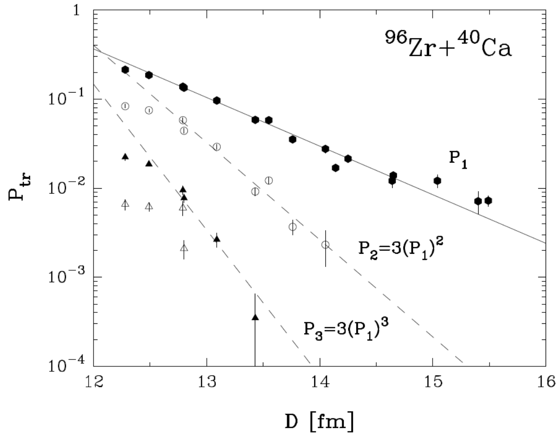

Fig. 1: Extracted transfer probabilities P_{tr} as function of the distance of closest approach *D* for neutron transfer channels

The two-neutron transfer channel has been analyzed with a semiclassical model that calculated, in the successive approximation, transitions to 0^+ states. Figure 2 shows the results of these calculations where the full line represents the inclusive transfer probability for one neutron transfer, the dotted line the ground state 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. It appears that the transfer probability for the transition to the excited 0^+ state in ^{42}Ca is much larger than the ground state one. But, by considering only 0^+ transitions the experimental cross section is underestimated by a factor of ~3. This

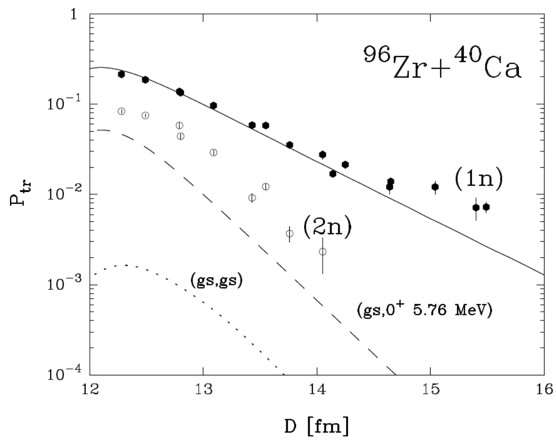

Fig. 2: Theoretical transfer probabilities for one- and two-particle transfer (lines) in comparison with the experimental data (points)

enhancement is ascribed to transitions to states with large angular momentum and to transitions of non-natural character, indicating that more complex two-particle correlations have to be considered in the transfer process.

In experimental conditions similar to those already successfully exploited in the $^{96}Zr+^{40}Ca$ case, as a further step we investigated the $^{116}Sn+^{60}Ni$ system whose ground to ground state Q-values are close to zero for neutron transfers, matching their optimum Q-value (~ 0 MeV). In particular, we measured the excitation functions in steps of 5 MeV from the Coulomb barrier (500 MeV) down to about 25% below (420 MeV) for the transfer channels populated in the inverse kinematics reaction. For this system one expects to have a main population close to the ground to ground state transitions and, in particular for the +2*n* channel, it is interesting to see how calculations including only transfer to the 0^+_{gs} states compare with the experimental data. The ^{116}Sn beam was delivered by the PIAVE injector and the ALPI superconducting booster with an average current of ~2 pnA onto a 100 μg/cm^2 ^{60}Ni target with a 15 μg/cm^2 C-backing. Ni-like recoils have been detected by PRISMA at θ_{lab}=20°, corresponding to $\theta_{c.m.}\simeq$140° and transfer yields have been measured down to ~ 16 fm of distance of closest approach. Figure 3 shows the Total Kinetic Energy Loss (TKEL) spectra for the elastic and one (+1*n*) and two (+2*n*) neutron pick-up channels at the representative bombarding energy of E_{lab} = 475 MeV, close to the Coulomb barrier. The elastic (+inelastic) peak has a width of ~ 3 MeV close to the expected energy resolution. The position of the Q-value for the elastic scattering (Q_{gs}=0) is marked with vertical dashed lines for the different channels in the figure. For neutron transfers (Q^{+1n}_{gs} = −1.7 MeV and Q^{+2n}_{gs} = +1.3 MeV) one observes a significant population close to these (ground to ground state) Q-values. At the same time one sees a tail toward larger TKEL, more marked for the +2*n* channel, typical of the energy regime close to the barrier. These energy loss components tend to disappear far below the barrier.

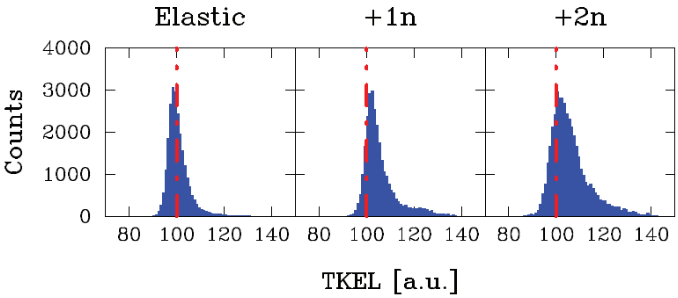

Fig. 3: TKEL loss spectra for the elastic and +1*n*, +2*n* transfer channels at the bombarding energy E_{beam} = 475 MeV. See text for details.

At present stage the data are being analyzed in the whole measured energy range, with the main aim to extract the transfer cross sections for the one and two neutron pick-up channels and for channels involving proton stripping. Proton stripping channels are in general more difficult to get experimentally far below the barrier since they drop off more rapidly than neutron channels, therefore a careful evaluation of the angular distribution (and transmission of the spectrometer) is mandatory. The −1*p* channel, together with the +1*n* channel, is one of basic building blocks defining the more complex multiple particle transfer and the comparison of its behaviour as a function of the bombarding energy with the microscopic calculations will tell about the shape of the form factors [11]. Part of the excitation functions for transfer channels have been measured with sufficient statistics to allow making cuts in the angular acceptance of PRISMA. In this way differential cross sections may be extracted for different angles at each energy, thus increasing significantly the number of points which define the transfer probability as a function of the distance of closest approach. Thus, a careful evaluation of the PRISMA response function is being studied via a Montecarlo simulation to assess the influence of the transport of the ions through the spectrometer on the measured yields. A successful application of these studies has been employed in the ^{48}Ca+^{64}Ni system [12, 13] where experimental angular distributions for elastic as well as for transfer channels, have been corrected for the response of the spectrometer. Such corrections involved a case where measurements have been performed at energies much higher than the Coulomb barrier and where deep-inelastic components contribute significantly to the yields. In the case of sub-barrier energies the Q-values are quite narrow and one expects that the effect of the transmission is relevant mostly at the edges of the spectrometer. The reconstructed experimental angular distribution for the elastic scattering at E_{lab} = 440 MeV, obtained applying the response function of the spectrometer to the experimental data, follows quite well the Rutherford scattering in almost the whole angular range, with the except of the extreme edges. Similar calculations are now being performed for the neutron transfer channels and for all other measured energies.

3 Particle-phonon states populated in multinucleon transfer reactions

The coupling of single particle degrees of freedom to nuclear vibration quanta is very important for the understanding of the transfer strength distribution. These effects, still largely unexplored, are essential for the description of many basic states in the vicinity of closed shells. To this end we studied the population of states with a particle-phonon character in neutron transfer channels produced in the ^{40}Ar+^{208}Pb reaction [14]. The ^{40}Ar beam was extracted from an ECR ion source and accelerated by means of the superconducting Linac ALPI at E_{lab} = 255 MeV onto a 300 μg/cm^2 ^{208}Pb target. The yields of the projectile like fragments have been measured with PRISMA at three different angles θ_{lab} = 46°, 54° ($\approx\theta_{\text{grazing}}$) and 59° in order to cover most of the transfer flux in the reaction. The coincident γ-rays were detected with the CLARA array, located in the hemisphere opposite to PRISMA. The normalization for the different measured angles was ensured by a silicon SSBD monitor detector positioned at a forward angle.

The γ spectra measured in coincidence with ^{40,41,42,43}Ar corresponding to inelastic scattering, +1*n*, +2*n* and +3*n* channels are plotted in Fig. 4. They contain transitions from particle states as well as from states involving combinations of single-particle with a collective boson. New transitions have

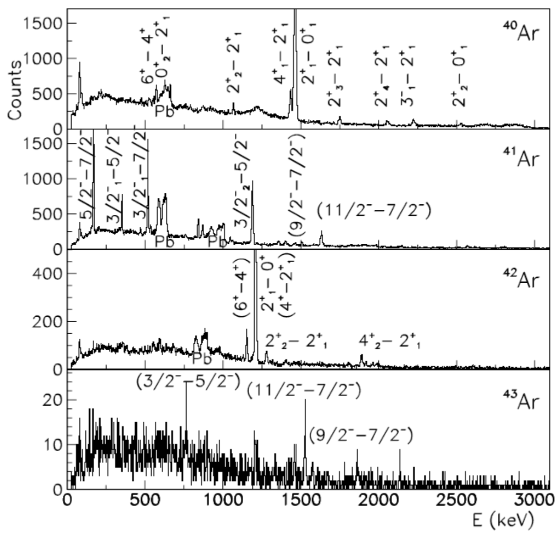

Fig. 4: Doppler corrected γ-ray spectra for ^{40,41,42,43}Ar

been identified in ^{41}Ar and ^{43}Ar ($9/2^- \rightarrow 7/2^-$ and $11/2^- \rightarrow 7/2^-$), and in ^{42}Ar ($6^+ \rightarrow 4^+$). A very strong population of the 2^+ states has been observed in ^{40}Ar and ^{42}Ar that act as cores in odd isotopes when a neutron is added. The energies, spins and parities of identified states agrees well with the results of *sd-pf* large-scale shell model (SM) calculations [15]. In ^{41}Ar and ^{43}Ar we observed, in addition to the known γ transitions of the low-lying states, strong lines at 1629.7(3) keV and at 1527.4(5) keV which we attribute to the population of the yet unknown $11/2^-$ states. These states 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). It is expected that the properties of these particle-phonon states are to a large extent determined by the properties of the corresponding phonon states.

Figure 5 shows the comparison of the measured and SM calculated energies for the 2^+ and $11/2^-$ states of argon isotopes in the N = 20 – 28 region evidencing an excellent agreement for all argon isotopes shell. Solid circles are SM calculated energies, open squares are the adopted levels, whereas open triangles and the cross symbol correspond to the energies of $11/2^-$ in ^{41}Ar and ^{43}Ar from our experiment and in ^{45}Ar from Ref. [16]. The behavior of their energies displays that the evolution of the collectivity, in the even isotopes (2^+ energies) and in the odd isotopes ($11/2^-$ energies), is very similar. This further corroborates the particle-phonon character of these $11/2^-$ states. We expect that heavy ion induced transfer reactions populate states of similar character in more neutron rich isotopes. Argon isotopes with N≥28 have been populated in ^{238}U+^{48}Ca reaction [17], and the populated states in the ^{47}Ar behave similarly to odd-argon isotopes discussed here.

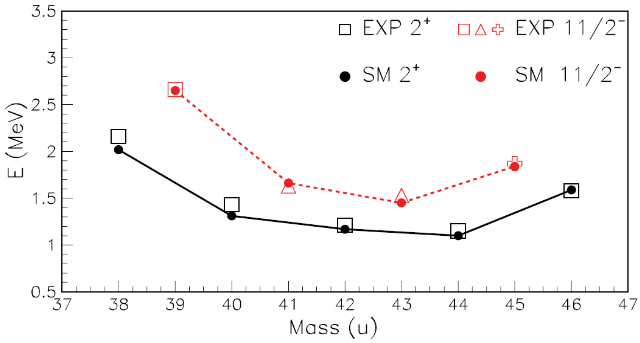

Fig. 5: Energies of the 2^+ and $11/2^-$ states of argon isotopes with N = 20–28

Experimental transfer yields have been interpreted within a reaction model [18] that explicitly treats the internal degrees of freedom of the two ions in terms of elementary modes, surface vibration and single particles. The significant population of particle-vibration 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.

4 An ancillary detector for the PRISMA spectrometer

A relevant aspect to be further investigated in transfer reactions that involves heavy ions is the influence of secondary processes, evaporation and fission that is important for the heavy partner. The determination of the survival probability against fission of heavy targetlike fragments (TLF) would help to understand how effectively multinucleon transfer reactions may be used to populate heavy nuclei [19]. We remark that data on the transfer induced fission are very scarce.

In order to check the relevance of the fission process in the population of the heavy fragments, we are planning to perform kinematical coincidence measurements where light fragments identified at the focal plane of PRISMA will be used to tag heavy partners entering into position sensitive device located at the correlation angle in the scattering chamber. To this end the magnetic spectrometer PRISMA is being equipped with a position sensitive detector composed of a single-sided silicon strip detector (SSSD) with a thickness of 300 μm and an active area of 5x5 cm^2. The detector (shown in Fig. 6) is segmented in 16 resistive strips providing X and Y position information, timing and energy

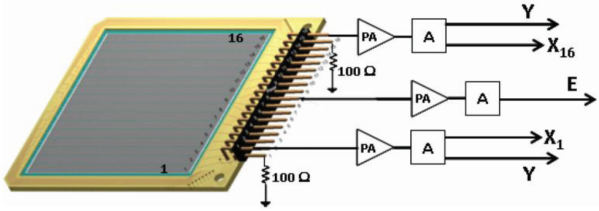

Fig. 6: Si strip detector for kinematical coincidence measurements

signals. In order to minimize the number of electronic channels, one end of each strip is grounded through a 100 Ω resistor and the position along the strip is obtained from the amplitude of the signal collected on the other end. Energy and position resolutions of about 80 keV and 1 mm along the strip, respectively, were obtained in laboratory tests performed with 5.486 MeV α particles.

A preliminary in-beam test has been performed by using the ^{40}Ca+^{90}Zr reaction at E_{lab} = 120 MeV. Figure 7 shows the X-Y scatter-plot (Zr ions) obtained with the entrance detector of PRISMA tagged by elastically scattered Ca ions entering into the SSSD. It was placed at 10 cm of

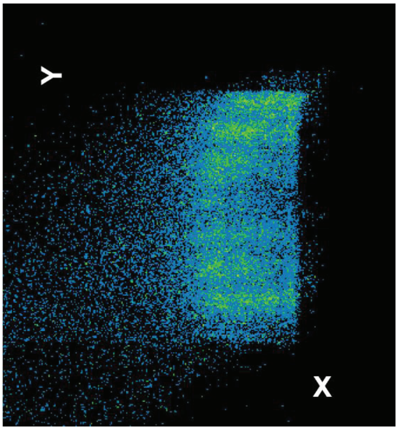

Fig. 7: X-Y plot measured with the start detector of PRISMA

distance from the target and covered with an aluminum mask composed of 8 by 10 holes, 1 mm diameter spaced 1.5 mm. Correlated Zr events in PRISMA cover only about half detector.

5 Summary

An enhancement by a factor 3 has been evidenced in the transfer probability extracted from the excitation function of the +2*n* transfer channel populated in the inverse kinematics reaction ^{96}Zr+^{40}Ca. Data analysis of the excitation functions for the main transfer channels populated in the ^{116}Sn+^{60}Ni reaction is in progress to deduce the cross sections and transfer probabilities for neutron pick-up channels as well as for channels involving proton stripping. The comparison between data and theory for both systems, namely superfluid and near closed shells nuclei, will significantly improve our understanding of nucleon-nucleon correlations in the transfer process. Excitation functions have been measured with sufficient statistics to extract angular distributions. Corrections of the experimental data based on the PRISMA response function are being performed for the neutron transfer channels.

In odd Ar isotopes populated via neutron transfer in the $^{40}Ar+^{208}Pb$ reaction, we observed a significant population of proposed $11/2^-$ states which well match a stretched configuration of the valence neutron coupled to the vibration quanta. The properties of such states are closely connected with the properties of the vibration quanta, allowing to follow the development of collectivity in odd argon isotopes.

A new ancillary detector for the PRISMA spectrometer has been developed and a preliminary in-beam test has been carried out. It will allow to perform kinematic coincidence measurements in order to study the effect of secondary processes such as the fission in the population of the TLF yields.

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