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Abstract. Large acceptance magnetic spectrometers, such as PRISMA installed at Laboratori Nazionali di Legnaro, gave a further boost to the renewed interest for multinucleon transfer reactions in the last decade. 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. Selected results obtained with the PRISMA-CLARA set-up in odd argon isotopes populated by using the multinucleon transfer process and in sub-barrier transfer measurements are presented in this contribution. The status of an ancillary detector which is being developed for PRISMA in order to perform kinematical coincidence measurements is also reported.

1. Introduction

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 [1]. The renewed interest in the last decade for multinucleon transfer reactions 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 [2, 3, 4] is the large acceptance magnetic spectrometer designed to be used with heavy-ion beams accelerated at energies up to \( E = 10.4 \) MeV by means of the Tandem-ALPI accelerator complex of LNL. It can operate as a standalone device or coupled to large γ-ray arrays such as the CLARA [5] set-up (until March 2008) or the AGATA Demonstrator (presently). 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 were mainly addressed to obtain information on the shell evolution and the onset of new regions of deformation (collectivity, critical point symmetries) in medium-mass moderately neutron-rich nuclei.

2. Population of particle-vibration states 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 $^{40}\text{Ar} + ^{208}\text{Pb}$ reaction [6]. The $^{40}\text{Ar}$ beam was extracted from an ECR ion source and accelerated by means of the superconducting Linac ALPI at $E_{\text{lab}} = 255$ MeV onto a 300 $\mu$g/cm$^2$ $^{208}\text{Pb}$ target. The yields of the projectile like fragments have been measured with PRISMA at three different angles $\theta_{\text{lab}}$ = 46°, 54° ($\approx$ $\theta_{\text{grazing}}$) and 59° in order to cover most of the transfer flux in the reaction. The coincident $\gamma$-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 $\gamma$ spectra measured in coincidence with $^{40,41,42,43}\text{Ar}$ corresponding to inelastic scattering, +1$n$, +2$n$ and +3$n$ channels are plotted in figure 1. They contain transitions from particle states as well as from states involving combinations of single-particle with a collective boson. New transitions have been identified in $^{41}\text{Ar}$ and $^{43}\text{Ar}$ (9/2$^-$ $\rightarrow$ 7/2$^-$ and 11/2$^-$ $\rightarrow$ 7/2$^-$), and in $^{42}\text{Ar}$ (6$^+$ $\rightarrow$ 4$^+$). A very strong population of the 2$^+$ states has been observed in $^{40}\text{Ar}$ and $^{42}\text{Ar}$ 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 [7]. In $^{41}\text{Ar}$ and $^{43}\text{Ar}$ we observed, in addition to the known $\gamma$ 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. $|2^+, (f7/2)^1>$ 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 2 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 $^{41}\text{Ar}$ and $^{43}\text{Ar}$ from our experiment and in $^{45}\text{Ar}$ from ref. [8].

![Figure 1. Doppler corrected $\gamma$-ray spectra for $^{40,41,42,43}\text{Ar}$.](image1.png)

![Figure 2. Energies of the 2$^+$ and 11/2$^-$ states of argon isotopes with N = 20–28.](image2.png)
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\(\geq 28\) have been populated in \(^{238}\)U\(^+\)\(^{40}\)Ca reaction [9], and the populated states in the \(^{47}\)Ar behave similarly to odd-argon isotopes discussed here.

Experimental transfer yields have been interpreted within a reaction model [10] 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.

3. Sub-barrier transfer measurements

In recent years there has been a growing interest in studying nuclear dynamics processes at energies well below the Coulomb barrier, in particular sub-barrier fusion reactions. This same energy range is also ideal to investigate transfer processes, which are strongly connected with fusion in an overlapping range of energies and angular momenta. In transfer reactions at sub-barrier energies nuclei 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 allow to extract more quantitative information on the mechanism of multiple transfer processes, in particular 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 target like fragments with magnetic spectrometers at very forward angles [11, 12].

We recently measured with the spectrometer PRISMA the excitation functions for the neutron transfer channels populated in the inverse kinematics \(^{96}\)Zr\(^+\)\(^{40}\)Ca reaction [13] from the Coulomb barrier (330 MeV) to \(\sim 25\%\) 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. The \(^{96}\)Zr beam was accelerated by the Tandem+ALPI accelerator complex of LNL onto a 50 \(\mu\)g/cm\(^2\) \(^{40}\)CaF\(_2\) target supported on a 15 \(\mu\)g/cm\(^2\) C backing. Mass spectra of the target like fragments, measured with magnetic spectrometer PRISMA placed at 20\(^\circ\), 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 \(P_\nu\) as function of the distance of closest approach \(D\), with \(P_\nu\) 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 fulfills 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 \(P_\nu(\theta) \approx e^{-2\alpha D(\theta)}\), where the parameter \(\alpha\) 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 vs the distance of closest approach \(D\) are thus represented (in a semi-logarithmic plot) by straight lines with a slope -\(\alpha\). Such behaviour is independent on 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 [12], and at lower energies where no anomaly in the slope behavior has been clearly identified [14].

The transfer probabilities extracted from the yields of the $+1n$, $+2n$ and $+3n$ transfer channels as a function of the distance of closest approach $D$ are shown in figure 3, together with the solid lines which are the results of the fitting procedure. Data for the $+4n$ channel 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 $P_n$ 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 $P_{3n} = 3(P_{1n})^3$.

The two-neutron transfer channel has been analyzed with a semiclassical model that calculated, in the successive approximation, transitions to 0$^+$ states. Figure 4 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 $\sim 3$. This 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.

![Figure 3](image1.png)  
**Figure 3.** Extracted transfer probabilities $P_n$ as function of the distance of closest approach $D$ for neutron transfer channels.

![Figure 4](image2.png)  
**Figure 4.** Theoretical transfer probabilities for one- and two-particle transfer (lines) in comparison with the experimental data (points).

### 4. A new 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 [15]. 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 cm². The detector is segmented in 16 resistive providing X and Y position information, timing and energy 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. The readout scheme of the detector is shown in figure 5. 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 40Ca+90Zr reaction at E_{lab} = 120 MeV. Figure 6 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 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.

**Figure 5.** Si strip detector for kinematical coincidence measurements.

**Figure 6.** X-Y plot measured with the start detector of PRISMA.

5. Summary

In odd Ar isotopes populated via neutron transfer in the 40Ar+208Pb 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. An enhancement by a factor 3 has been evidenced in the transfer probability extracted from the excitation function of the +2n transfer channel populated in the inverse kinematics reaction 96Zr+40Ca. A new ancillary detector for the PRISMA spectrometer will allow to study the effect of secondary processes such as the fission in the population of the TLF yields.

6. References