Multinucleon transfer reactions in the ^{40}Ca+^{96}Zr system measured by PRISMA+CLARA

S. Szilner[1,2], L. Corradi[1], G. Pollarolo[3], S. Beghini[4], A.M. Stefanini[1], N. Mărginean[1], C.A. Ur[4], E. Farnea[4], E. Fioretto[1], A. Gadea[1], F. Haas[5], A. Latina[1], S.M. Lenzi[4], R. Mărginean[4], G. Montagnoli[4], D.R. Napoli[1], I.V. Pokrovsky[1], F. Recchia[4], M. Romoli[6], M.-Đ. Salsac[5], F. Scarlassara[4], N. Soić[2], M. Trotta[6], Q. Zhong[1]

1 INFN, Laboratori Nazionali di Legnaro, 2 Ruđer Bošković Institute, Zagreb, Croatia, 3 Università di Torino, and Istituto Nazionale di Fisica Nucleare, Torino, 4 Università di Padova, and Istituto Nazionale di Fisica Nucleare, Padova, 5 Institut de Recherches Subatomiques, CNRS-IN2P3/ULP, Strasbourg, France, 6 Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli

INTRODUCTION

Quasi-elastic and deep inelastic processes have been extensively studied, theoretically and experimentally, during the past twenty years. However, only in recent studies, thanks to the development of efficient spectrometers, a complete identification of the final reaction products has been achieved up to the pick-up and stripping of several neutrons and protons [1–3]. What makes this field of research so rich is the fact that the nuclei brought into a close contact manifest the degrees of freedom associated to the single-particle motion, as well as those associated to strong surface vibration and rotations. Thus, multinucleon transfer between heavy ions at energies close to the Coulomb barrier represents the region where nuclear structure still strongly influences the reaction dynamics. The comparison between data and calculations, based on semiclassical models [4, 5], allowed to quantitatively study how degrees of freedom of different complexity act in the transfer process.

Closed shell nuclei constitute an almost ideal case for such quantitative comparison with calculations. Therefore, we have studied multinucleon transfer processes for the system ^{40}Ca+^{96}Zr close to the Coulomb barrier, in a particle-γ coincidence experiment.

EXPERIMENTS AND EXPERIMENTAL RESULTS

The experiment was performed using the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro. A ^{40}Ca beam was accelerated onto a ^{96}Zr target, at E_{lab}=152 MeV, an energy close to the Coulomb barrier. Projectile-like fragments were detected with the magnetic spectrometer PRISMA [6]. The coincident γ rays were detected with the CLARA array [9].

The main features of PRISMA are its large solid angle of 80 msr, wide momentum acceptance $\pm$10%, and mass resolution of 1/300 achieved via trajectory reconstruction. The ion mass is determined from the information on the (θ,ϕ) entrance angles, (X, Y) exit positions, TOF

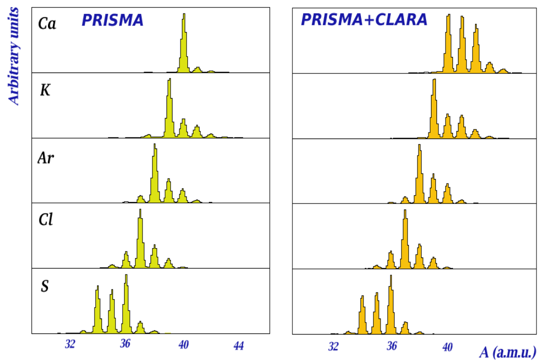

FIG. 1: *Figure shows the mass distribution (up to −4p channels) obtained in the reaction ^{40}Ca+^{96}Zr at $E_{\rm lab}$ =152 MeV and at the grazing angle, with (right) and without (left) γ coincidences.*

signal and total energy. The entrance detector is a position sensitive micro-channel plate, which provides the position signals and the start signal for TOF [7]. Ions pass through the optical elements of the spectrometer, a quadrupole singlet and a magnetic dipole, and enter into the focal plane detector [8]. The focal plane detector is an array of parallel plates of multiwire-type, providing a stop for TOF and (X, Y) position signals, followed by an array of transverse field multiparametric ionization chambers, providing ΔE and total energy signals. Gamma rays following the de-excitation of reaction products were detected with the CLARA array [9], composed of 25 Clover detectors, forming a 2π configuration close to the target position.

A clear identification of the nuclear charge and mass of projectile-like fragments is obtained up to 8 proton stripping and 6 neutron transfer. A mass resolution of $\simeq$1/280, has been obtained, which is consistent with the characteristics of the spectrometer. The mass distribution measured at the grazing angle, without (left) and with γ coincidences (right) is plotted on Fig. 1. Different yields are observed in the case of the mass distributions in coincidence with the γ rays due to the different Q-value regions populated for different channels and γ multiplicities. The mass distributions indicate the dominance of a direct mechanism where nucleon transfer follows the path expected from optimum Q-value arguments that favor neutron pick-up and proton stripping, for stable nuclei. We notice also that for massive proton transfer channels the isotopic distribution drifts towards lower masses, indicating that evaporation processes influence the final isotopic distributions. In the present particle-gamma coincidence experiment it is possible to quantitatively determine the influence of evaporation.

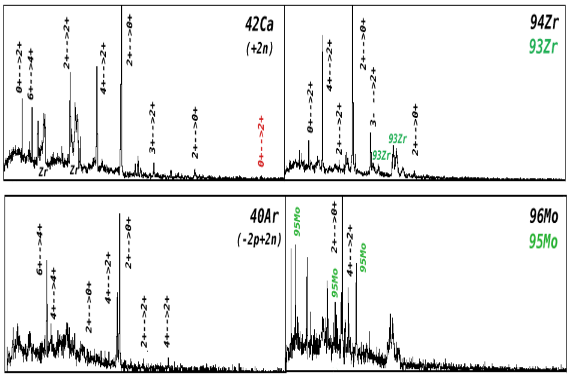

FIG. 2: *γ-ray spectra of the light (left) and heavy (right) reaction partners of the $+2n$ and $-2p+2n$ channels of the ^{40}Ca+^{96}Zr reaction. The top (bottom) panel shows the γ-ray spectra obtained by gating on $Z = 20$ ($Z = 18$) and $A = 42$ ($A = 40$). Strong transitions are marked on the figure.*

Fig. 2 shows γ spectra of the $+2n$ and $-2p+2n$ channels of the light and of the heavy reaction partner. The single coincidence γ spectra of the light partner are obtained after Doppler correction for the projectile-like nuclei selected by the spectrometer. The final resolution of γ peaks at $\simeq$1.5 MeV is $\simeq$ 1%. The same quality of the γ spectra is observed for the large range of nuclides populated in this multinucleon transfer reaction. The γ spectra of the heavy partner have been extracted assuming binary processes, and the heavy evaporated isotopes have been identified via their characteristic γ lines. As can be appreciated from the figure, the dominant populated states are yrast states, pointing to the ability of the multinucleon transfer reactions to transfer a large amount of angular momenta.

In the comparison with the theoretical models (Complex WKB calculations) to obtain the yields of the massive charge transfer channels, the evaporation from the primary fragments is included taking into account the calculated excitation energies of fragments and their intrinsic angular momenta. The data analysis of the obtained evaporation cross sections and the comparison with the CWKB calculations are in progress.

Once the projectile-like reaction fragments are identified by their mass, charge and energy, through the kinematic relations we can calculate the trajectories and energies of the target-like fragments, assuming binary processes. The left side of fig. 2 depicts the γ-ray spectra where the Doppler correction has been carried out for the target-like fragments. Besides the γ transitions which correspond to the heavy binary partner, in the spectra we can identify several γ lines which correspond to the one, two, and even three neutrons evaporation from the heavy partner. It is clear that the process of evaporation becomes more and more important as more and more nucleons are transferred. In the case of the massive proton stripping channels, the characteristic lines of the primary heavy partner tend to vanish, while the cross sections of the $-1n$ and $-2n$ channels become dominant.

In this report we have presented results of multinucleon transfer reactions studied in the ^{40}Ca+^{96}Zr (particle-γ coincidence) system at energies close to the Coulomb barrier. In the comparison with the semiclassical models we learned that besides the well known surface modes and the one-particle transfer channels, the process of evaporation is important in the description of the isotopic distribution of the reaction products.

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[1] S. Szilner et al., *Phys. Rev. C* **71**, 044610 (2005); *Eur. Phys. J. A* **21**, 87 (2004).
[2] L. Corradi et al., *Phys. Rev. C* **C63**, 021601R (2001); *Phys. Rev. C* **66**, 024606 (2002).
[3] C.L. Jiang et al., *Phys. Lett. B* **337**, 59 (1994); *Phys. Rev. C* **57**, 2393 (1998).
[4] A. Winther, *Nucl. Phys. A* **572**, 191 (1994); *Nucl. Phys. A* **594**, 203 (1995).
[5] C.H. Dasso, and G. Pollarolo, and A. Winther, *Phys. Rev. Lett.* **73**, 1907 (1994).
[6] A.M. Stefanini et al., *Nucl. Phys. A* **701**, 217c (2002).
[7] G. Montagnoli et al., *Nucl. Instr. and Meth. in Phys. Res. A* **547** 455 (2005).
[8] S. Beghini et al., *Nucl. Instr. and Meth. in Phys. Res. A* **551** 364 (2005).
[9] A. Gadea et al., *Eur. Phys. J. A* **20**, 193 (2004).