Vol. 40 (2009) ACTA PHYSICA POLONICA B No 3

HEAVY ION TRANSFER REACTIONS STUDIED WITH PRISMA+CLARA*

L. Corradi[a], S. Szilner[a,c], G. Pollarolo[d], S. Beghini[b]
E. Fioretto[a] B. Guiot[a], N.M. Marginean[a,e], P. Mason[a]
G. Montagnoli[b], F. Scarlassara[b], R. Silvestri[a], A.M. Stefanini[a]
E. Farnea[b], C.A. Ur[b], S. Aydin[a]
G. de Angelis[a], A. Gadea[a], R. Orlandi[a], S. Lunardi[b]
R. Marginean[b,c], D. Mengoni[b], D.R. Napoli[a] C. Mihai[e]
F. Recchia[b], E. Sahin[a], N. Soić[c], D. Jelavić[c]
J.J. Valiente-Dobon[a], F. Della Vedova[b]

[a]INFN, Laboratori Nazionali di Legnaro
[b]Dipartimento di Fisica and INFN, Padova
[c]Ruder Bošković Institute, Zagreb, Croatia
[d]Dipartimento di Fisica Teorica, Univ. di Torino, and INFN, Torino
[e]National Institute for Physics and NE, Bucharest, Romania

(Received October 30, 2008)

The large solid angle magnetic spectrometer PRISMA coupled to the γ array CLARA represents a significant step forward in the field of binary reactions at energies close to the Coulomb barrier. With this set-up extensive investigations have been carried out for nuclear structure and reaction dynamics. Via γ-particle coincidences it is now experimentally possible to measure the transfer strength to specific final states with high efficiency. In reactions with heavy ions, one can populate states of high angular momentum and, at the same, one can probe the population of specific nuclear levels via transfer of multiple pairs. Valuable information about the structure of those states can be then derived from the study of their decay modes. In the present paper aspects of these studies will be presented, focusing more closely on the reaction mechanism, in particular on the properties of quasi-elastic and deep-inelastic processes and on nucleon–nucleon correlations at energies far below the Coulomb barrier. We concentrated on (near) closed shell systems as they allow a better quantitative comparison between experiment and theory.

PACS numbers: 25.70.Hi, 29.30.Aj, 24.10.–i, 23.20.Lv

* Presented at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

1. Introduction

With the development of high resolution and high efficiency experimental set-up's, one could unambiguously detect in mass and charge the nuclei produced in multineutron and multiproton transfer reactions (see [1, 2] and references therein). The advent of the last generation large solid angle magnetic spectrometer PRISMA [3] pushed the detection limit more than an order of magnitude below, with a significant gain in mass resolution for very heavy ions. Further, the coupling of this spectrometer to the large gamma array CLARA [4] allowed to perform γ-particle coincidences, thus detecting the transfer strength to the lowest excited levels of binary products and performing gamma spectroscopy for nuclei moderately far from stability produced via nucleon transfer or deep-inelastic reactions, especially in the neutron-rich region.

In this paper we focus on specific aspects of reaction mechanism studies being performed with PRISMA. In particular we outline how details on the transfer process can be revealed by exploiting γ-particle coincidences. For the results concerning pure nuclear structure studies we refer to the contribution [5] to this conference.

2. Elastic scattering

Elastic scattering is important to learn about the (outer part of) the nuclear potential and provides essential information on absorptive effects, to be accounted for in coupled channel calculations. The present set-up offers the possibility to separate elastic from inelastic scattering. The pure elastic scattering can be determined by comparing the events with and without γ coincidences [6]. As an example, in the top panel of Fig. 1 are shown the total kinetic energy loss (TKEL) spectra for ^{90}Zr in the reaction ^{90}Zr+^{208}Pb with and without γ coincidence, normalized in the tail (large TKEL) region. By subtraction, we obtain the contribution of pure elastic. This subtracted spectrum is characterized by a narrow peak centered at TKEL $\simeq 0$ MeV with a FWHM of 2.65 MeV. Moreover, its centroid is separated by 2.15 MeV from the maximum of the TKEL spectrum in coincidence with CLARA, whose value is very close to the inelastic excitation of the first 2^+ state in ^{90}Zr. Such a procedure should be reliable, provided that the shape of the spectrum in coincidence with γ-rays only weakly depends on the γ multiplicity. This fact is fulfilled for nuclei having low level density close to the ground state and rather narrow ($\simeq$ 2–3 MeV) TKEL distributions, as for the present near closed-shell nuclei.

By repeating this subtraction in steps of one degree over the entrance angular range ($\Delta\theta_{\rm lab} = 12°$) of PRISMA one obtains the elastic angular distribution whose ratio to Rutherford is shown in the bottom panel of Fig. 1, in comparison with the results of GRAZING calculations [7]. The very pronounced fall-off of the elastic cross section for large angles clearly indicates that the elastic scattering for this system is dominated by strong absorption. The good agreement between theory and experiment gives us confidence on the used potential and on the fact that the included reaction channels correctly describe the depopulation of the entrance channel (absorption).

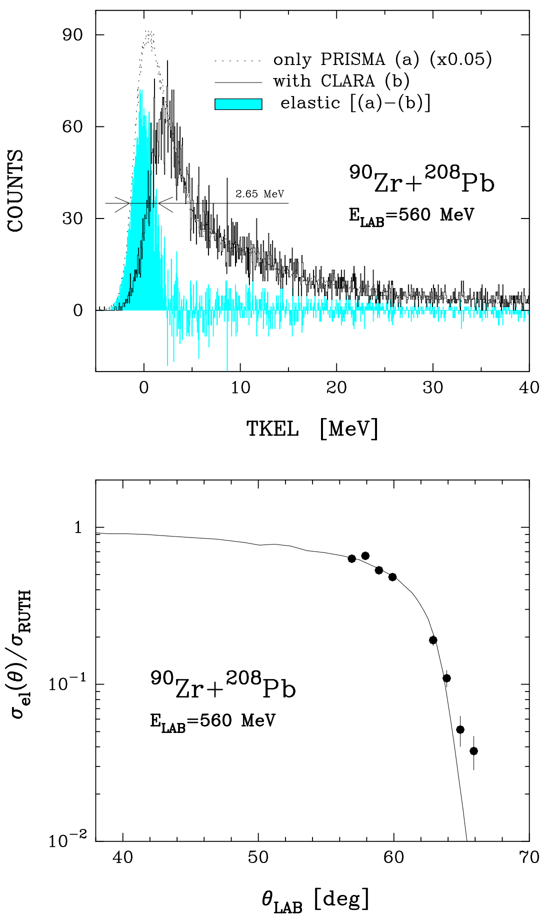

Fig. 1. Top: Experimental angle integrated total kinetic energy loss distributions (TKEL) for ^{90}Zr in the ^{90}Zr+^{208}Pb reaction (a) without coincidence with γ-rays and (b) with at least one γ-ray detected in CLARA. The two spectra are normalized in such a way that the high TKEL tails match. The gray area corresponds to the subtraction between the two spectra [(a)–(b)], giving a peak whose width is $\sim$ 2.65 MeV. Bottom: Experimental (points) and GRAZING calculated (curve) differential cross section for elastic scattering, normalized to Rutherford. Only statistical errors are included.

3. Pairing vibrations

Closed-shell systems are well suited for the identification of states reached via the addition and/or the removal of pairs of nucleons. Those states have been studied with light ion reactions and formed the basis for the identification of pairing vibration degrees of freedom in the nuclear medium [8]. In a previous experiment with ^{40}Ca+^{208}Pb (*cf.* [9] and references therein) we have noticed that in order to obtain a good description of the experimental total cross sections for the different isotopes populated in the reaction one has to include, in the theoretical model, the degrees of freedom related to the transfer of pairs of nucleons, both protons and neutrons. These degrees of freedom are treated as pair-vibrational modes and for their excitation we have used the form factors as provided by the macroscopic model [10]. The influence of these degrees of freedom is particularly visible in the proton sector since the cross sections of proton stripping channels are much smaller than the neutron pick-up ones.

To have evidence of the excitation of these modes in the neutron sector we have analyzed in detail [9] the total kinetic energy loss (TKEL) spectra of ^{42}Ca, the two neutron pick-up channel. Here most of the cross section is concentrated in a pronounced peak at an energy that is compatible with the excitation of a group of 0^+ states at ~ 6 MeV where a pairing-vibrational state should be located [8].

The present set-up should allow the observation of the decay pattern of the populated 0^+ states. In Fig. 2 we show the γ-spectrum for ^{42}Ca obtained in the reaction ^{40}Ca+^{96}Zr. We observe here (see expanded region) a γ transition at 4340 keV which is consistent with a decay from a level at 5.8 MeV to the 2_1^+ state. The limited statistics accumulated for this transition (we remark that such high energy γ-rays have a low photo-peak efficiency) does not allow to deduce the spin of the populated level, though

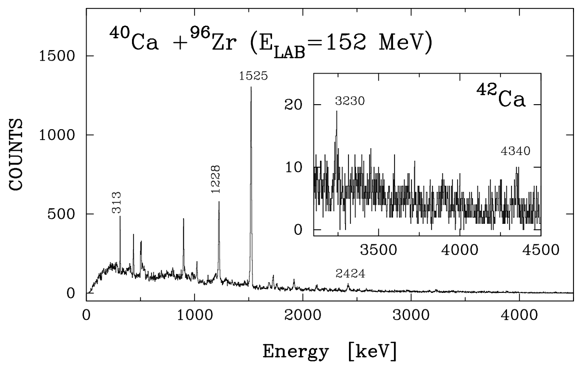

Fig. 2. γ-ray spectrum with expanded region in inlet for ^{42}Ca obtained in the ^{40}Ca+^{96}Zr reaction.

the distribution over the rings of CLARA shows an isotropic pattern but with very large error-bars. In the expanded γ spectrum we also observe a γ transition of 3230 keV, which is the main branch of the decay from the 2^+ state at 4760 keV, strongly populated in (t,p) reactions [11].

4. From quasi-elastic to deep-inelastic regime

The Z and A identification capability and the large detection efficiency of PRISMA allows to follow the evolution of the reaction from the quasi elastic (*i.e.* few nucleon transfer and low TKEL) to the deep inelastic regime (*i.e.* many nucleon transfer and large TKEL). Here, the challenging question is to what extent the fundamental degrees of freedom (single particle, surface and pair modes) used to describe few nucleon transfer processes, holds in the presence of large energy losses and/or large number of nucleons.

In Fig. 3 we show the TKEL spectra obtained in the ^{90}Zr+^{208}Pb reaction [12] for different transfer channels. One can follow the evolution pattern as function of the number of transferred neutrons and protons. For instance,

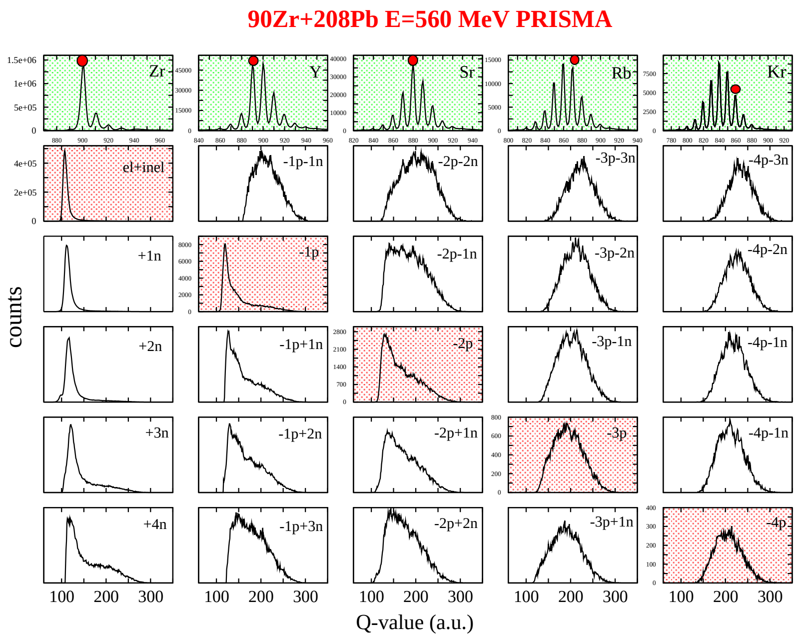

Fig. 3. TKEL spectra obtained in the reaction ^{90}Zr+^{208}Pb for the indicated transfer channels. In the top row are shown the mass distribution associated to the different nuclear charges, while the circles indicate the specific masses corresponding to the spectra displayed along the upper-left/lower-right diagonal. The centroid of the elastic+inelastic channel corresponds to $Q = 0$. The scale of the Q-value axis is 1 MeV/channel.

in the case of pure neutron transfer one sees a quasi-elastic peak and an increasing strength on large energy loss components when adding neutrons. We remind that with PRISMA one detects secondary fragments and that the TKEL spectra are constructed assuming binary reactions. For channels which, due to optimum Q-values, are not directly populated, the shape of the corresponding TKEL differ a lot from the smooth behaviour just described. Look for instance at the comparison between the $(-1p+1n)$ channel (mainly directly populated) and the $(-1p-1n)$ one. This different behaviour tends to smooth out with larger number of transferred protons.

Large energy losses are associated with nucleon evaporation from the primary fragments. This can be clearly seen with PRISMA+CLARA [6]. Gating with PRISMA on a specific Z and A (light partner) the velocity vector of the undetected heavy partner can be evaluated and applied for the Doppler correction of its corresponding γ-rays. In those spectra not only the γ-rays belonging to the primary binary partner are present but also the ones of the nuclei produced after evaporation takes place. For example in the ^{40}Ca+^{96}Zr reaction, for the $-2p+2n$ channel about 60% of the yield corresponds to ^{96}Mo, while the rest is equally shared between isotopes corresponding to the evaporation of one and two neutrons.

In general, for few nucleon transfer channels most of the yield corresponds to the true binary partner. This behavior is closely connected with the observed TKEL. For the neutron pick-up channels the major contribution in the TKEL is close to the optimum Q values ($Q_{\rm opt} \simeq 0$), while in the proton stripping channels larger TKEL are observed, thus the neutron evaporation has a stronger effect on the final mass partition. The importance of neutron evaporation in the modification of the final yield distribution was outlined in inclusive measurements [1, 2]. A direct signature of this effect was observed by correlating projectile-like and target-like fragment isotopic yields via γ–γ coincidences [13].

5. Sub-barrier transfer reactions

In recent years there has been growing interest in studying dynamic processes at energies well below the Coulomb barrier, in particular sub-barrier fusion (see Refs. [14,15] and references therein for the last conferences on the subject). This same energy range is also ideal to investigate transfer processes, which are strongly connected with fusion, as they probe different but complementary ranges of nuclear overlap.

The transfer cross section can be written as:

$$\sigma_{\rm tr} \sim e^{-\frac{2}{\hbar}\int W(r(t))dt} \sum \left| \int F_{if}(r(t)) e^{i\omega_{if}} dt \right|^2 ,$$

where the first exponential term gives the probability to remain in the elastic channel and the second describes the direct population of the transfer channels being $F(r)$ the transfer form factor with the sum running over all the final channels. The integrals are performed along the Coulomb trajectory. The imaginary potential $W(r)$, that describes the depopulation of the entrance channel, at very low energies is dominated by the single-nucleon transfer channels. Since the Q-value distributions get narrower at low bombarding energies these subbarrier studies may provide important information on the nuclear correlation close to the ground state. In this energy region the multinucleon transfer channels should be dominated by a successive mechanism with negligible contribution from a cluster-like transfer [16]. This fact should provide a simpler analysis of the data.

From the experimental point of view, measurements of heavy-ion transfer reactions at far sub-barrier energies have significant technical difficulties. At low bombarding energies angular distributions result, in the center of mass frame, in a strong backward peaking, with a maximum at $\theta_{\rm cm} \simeq 180°$. The absolute yield gets very small, therefore high efficiency is needed. At the same time, mass and nuclear charge resolutions must be maintained at a level sufficient to distinguish the different reaction channels. For situations where the projectile has a significant fraction of the target mass, as it is in most cases, the backscattered projectile-like fragment has such a low energy that usual identification techniques become invalid. A suitable way to overcome these limitations is by means of inverse kinematics, thus we recently detected multinucleon transfer channels in the reaction ^{94}Zr+^{40}Ca at different bombarding energies below the Coulomb barrier [17], making use of the PRISMA+CLARA set-up. The use of inverse kinematics and the detection at very forward angles, allowed to have, at the same time, enough kinetic energy of the outgoing recoils (for energy and therefore mass resolution) and forward focused angular distribution (high efficiency). Sub barrier fusion cross sections for the same system had been previously measured with high precision [18] and a complete set of data for both multinucleon transfer and fusion reactions would provide an excellent basis for coupled channel calculations.

In Fig. 4 we display the cross sections at $E_{\rm lab} = 314$ MeV computed with the code GRAZING [7] for the channels corresponding to Ca, K and Ar isotopes. For the pure $+1n$ transfer channels the angular distribution is also shown, one notices how the maximum of the differential cross section peaks at very forward laboratory angles (very backward angles in the center of mass).

In Fig. 5 we show the mass spectra for pure neutron transfer channels obtained after trajectory reconstruction at the four bombarding energies. While at the higher energy one observes the populations of up to four nucleon transfer, at the lower energy (below the Coulomb barrier) only one and two

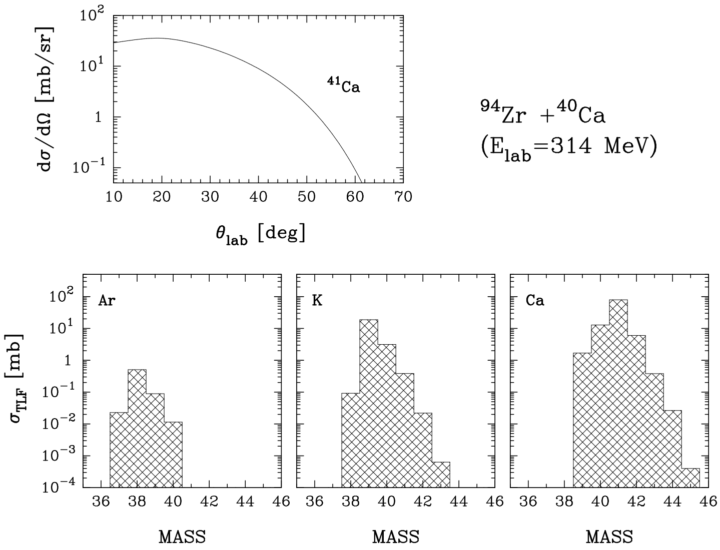

Fig. 4. Theoretical differential cross sections for the $+1n$ channel (top) and total cross sections for Ca, K, and Ar isotopes (bottom) for the ^{94}Zr+^{40}Ca reaction. Calculations have been performed with the code GRAZING.

neutron transfer survive. The mention that the Q-value distributions for the $+2n$ channel at the lowest energies are very narrow and close to the ground state to ground state transition, as a result of the very low excitation

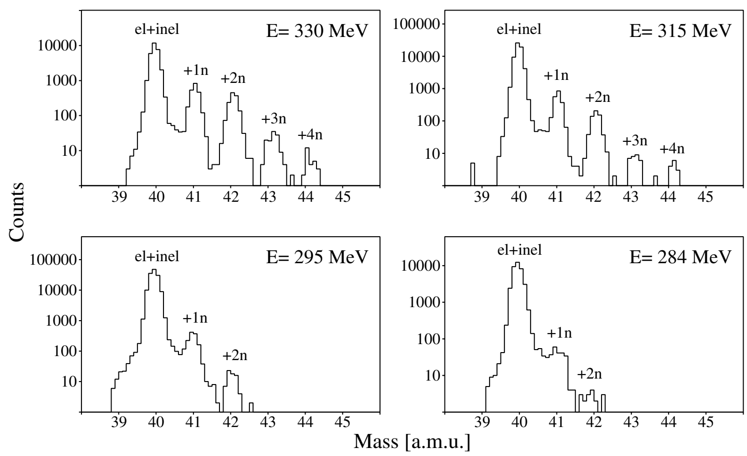

Fig. 5. Mass distributions for pure neutron transfer channels obtained in the reaction ^{94}Zr+^{40}Ca at the indicated bombarding energies. Ca-like recoils have been detected at θ_{lab}=20° with the PRISMA spectrometer.

energy of the transfer reaction products at these sub-barrier energies. The experimental results will be compared with coupled channel calculations, in particular the comparison of two nucleon *versus* one nucleon transfer should provide information on nucleon–nucleon correlation effects.

6. Summary and conclusions

We presented a selection of recent results of reaction mechanism studies carried out at LNL with the PRISMA spectrometer coupled to the CLARA γ array. We showed how details on the transfer process can be revealed by exploiting γ-particle coincidences, for the study of elastic scattering, pair vibrational states and the transition from quasi-elastic to deep inelastic processes. Very recent results have been also described on new experiments performed on transfer reactions in inverse kinematics to investigate nucleon–nucleon correlation effects at very low bombarding energies.

REFERENCES

[1] L. Corradi, G. Pollarolo, *Nucl. Phys. News* **15**, No. 4 (2006).
[2] S. Szilner *et al., Phys. Rev.* **C71**, 044610 (2005).
[3] A.M. Stefanini *et al.*, Proposta di esperimento PRISMA, LNL-INFN (Rep)-120/97 (1997); *Nucl. Phys.* **A701**, 217c (2002); `http://www.lnl.infn.it/~prisma`.
[4] A. Gadea *et al., Eur. Phys. J.* **A20**, 193 (2004).
[5] E. Farnea *et al., Acta Phys. Pol. B* **40**, 467 (2009) these proceedings.
[6] S. Szilner *et al., Phys. Rev.* **C76**, 024604 (2007).
[7] A. Winther, *Nucl. Phys.* **A572**, 191 (1994); *Nucl. Phys.* **A594**, 203 (1995); GRAZING program, `http://www.to.infn.it/~nanni/grazing`.
[8] R.A. Broglia, O. Hansen, C. Riedel, *Advances in Nuclear Physics*, Ed. M. Baranger and E. Vogt, Plenum Press, New York 1973, Vol. 6, p. 287.
[9] S. Szilner *et al., Eur. Phys. J.* **A21**, 87 (2004).
[10] G. Pollarolo *et al, Nucl. Phys.* **A406**, 369 (1983).
[11] D.C. Williams *et al., Phys. Rev.* **164**, 1419 (1967).
[12] L. Corradi, *Nucl. Phys.* **A787**, 134 (2007).
[13] R. Broda, *J. Phys. G* **32**, R151 (2006).
[14] Fusion06: International Conference on Reaction Mechanisms and Nuclear Structure at the Coulomb Barrier, S. Servolo (Venezia), Italy, March 19–23, 2006, *AIP Conf. Proc.* Vol. 853, Melville (New York), L. Corradi *et al.* Eds.
[15] Fusion08: International Conference on New Aspects of Heavy Ion Collisions Near the Coulomb Barrier, Chicago, USA, September 22–26, 2008, *AIP Conf. Proc.* to be published, B.B. Back *et al.* Eds.
[16] B.F. Bayman, J. Chen, *Phys. Rev.* **C26**, 1509 (1982).
[17] L. Corradi, S. Szilner *et al.*, LNL-INFN PAC Proposal July 2007, July 2008.
[18] A.M. Stefanini *et al., Phys. Rev.* **C76**, 014610 (2007).