Recent results in multinucleon transfer reactions studied with PRISMA+CLARA

L.Corradi
INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy

Abstract

With the large solid angle magnetic spectrometer PRISMA coupled to the γ array CLARA extensive investigations have been carried out for nuclear structure and reaction dynamics. 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 measurements at energies far below the Coulomb barrier.

1 Introduction

Multinucleon transfer reactions at Coulomb barrier energies is an important field of research in low energy heavy-ion physics [1]. Through this mechanism one can in fact investigate nucleon-nucleon correlation in nuclei, the transition from the quasi-elastic to the deep-inelastic regime and channel coupling effects in sub-barrier fusion reactions. Different aspects of the correlation between reaction channels have been extensively discussed at the recent Fusion06 [2] and Fusion08 [3] conferences. An important and still poorly investigated question is what are the relevant degrees of freedom acting in the transfer process, i.e. single nucleon, pair or even cluster transfer modes. Thanks to the development of high resolution and high efficiency experimental set-up's, one could recently unambiguously detect in mass and charge the nuclei produced in transfer reactions up to the pick-up of six neutrons and the stripping of six protons (see e.g. [4, 5] and references therein). The advent of the last generation large solid angle magnetic spectrometer PRISMA [6] allowed to increase the detection limit by more than an order of magnitude, with a significant gain in mass resolution for very heavy ions. Further, the coupling of this spectrometer to the large gamma array CLARA [7] allowed to perform gamma-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. These studies are of primary importance for reactions to be done with radioactive ion beams, where multinucleon transfer has been shown to be a competitive tool for the study of neutron-rich nuclei, at least for certain mass regions. In this paper I will focus on specific aspects of reaction mechanism studies being performed with PRISMA. For the results concerning pure nuclear structure studies please refer to the contributions [8] 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, at least for some nuclei. The pure elastic scattering can be determined by comparing the events with and without γ coincidences [9]. 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, one obtains 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. By repeating this subtraction in steps of one degree over the entrance angular range

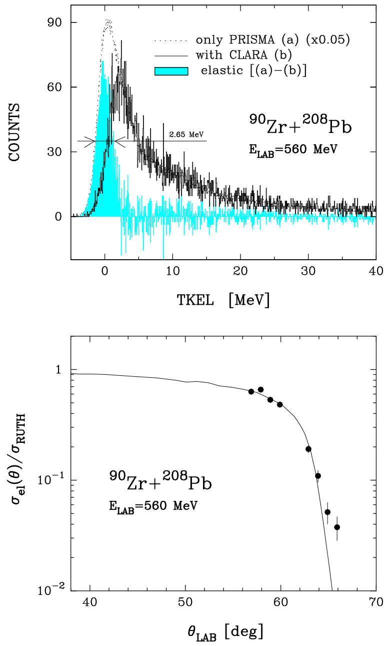

Fig. 1: Top: Experimental angle integrated total kinetic energy loss distributions (TKEL) for ^{90}Zr in the ^{90}Zr+^{208}Pb reaction (a) without coincidence with γ rays and (b) with at least one γ ray detected in CLARA. The two spectra are normalized in such a way that the high TKEL tails match. The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

($\Delta\theta_{\rm lab} = 12°$) 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 [10] (see also next section). 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). A similar kind of analysis has been successfully performed for the ^{48}Ca+^{64}Ni system [11].

3 Total cross sections

Total angle and Q-value integrated cross sections for multineutron and multiproton transfer channels have been investigated in various systems close the Coulomb barrier. Recently, such measurements have been extended with heavy ions detected in PRISMA, for instance in the reactions ^{90}Zr+^{208}Pb and ^{40}Ca+^{96}Zr [9, 12]. Both projectiles and targets are closed shell and therefore ideal candidates for a quantitative comparison with theoretical models [13,14]. One observes events corresponding to the pick-up as well as the (weaker) stripping of neutrons. Isotope identification in the proton transfer direction is visible down to $(-8p)$ stripping, but sensitivity was sufficient to observe even more proton stripping channels. I remind that in the quasi-elastic regime only proton stripping and neutron pick-up are favourite from optimum Q-value arguments. Fig. 2 shows as an example the experimental total cross sections for the pure neutron pick-up channels in ^{90}Zr+^{208}Pb and ^{40}Ca+^{96}Zr systems and the channels involving the one proton stripping in ^{40}Ca+^{96}Zr. The data are compared with calculations performed with the semiclassical code GRAZING [10]. The treatment of the transfer degrees of freedom is based on the

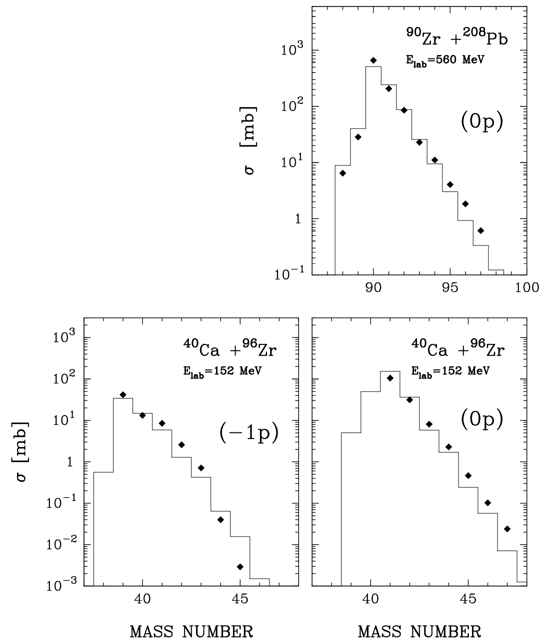

Fig. 2: Total cross sections for pure neutron pick-up channels in the ^{90}Zr+^{208}Pb reaction. Bottom: Total cross sections for pure neutron pick-up (right panel) and one-proton stripping (left panel) channels in the ^{40}Ca+^{96}Zr reaction. The points are the experimental data and the histograms are the GRAZING code calculations (see text).

assumption that in a heavy-ion collision the exchange of a nucleon proceeds via many open channels that are all quite weak, so that they may be treated independently. GRAZING treats surface degrees of freedom and particle transfer on the same footing, the exchange of many nucleons proceeds via a multi-step mechanism of single nucleons (both, protons and neutrons, via stripping, and pick-up processes). The trajectory is calculated by solving the system of classical equations for the variables of relative motion and the deformation parameters for the surface modes. The model includes the low-lying 2^+ and 3^- states of both projectile and target and the corresponding giant resonances. This model has been successfully applied in the description of multinucleon transfer reactions and can reproduce the near-barrier fusion excitation functions [15] and extracted barrier distributions [16].

Looking at the experimental data of Fig. 2 one finds that the cross sections for the neutron pick-up drop by almost a constant factor for each transferred neutron, as an independent particle mechanism would suggest. The comparison with calculations supports this idea, one notices a remarkable agreement both on the neutron pick-up as well as on the neutron stripping side. One can mention that the pure proton cross sections behave differently, with the population of the -2p channel as strong as the -1p. This suggests the contribution of processes involving the transfer of proton pairs in addition to the successive transfer of single protons. One also oberves that as more protons are transferred the average mass shifts to lower neutron number. This is attributed, at least partly, to the effect of neutron evaporation from the primary fragments. This effect of neutron evaporation is indirectly visible from the analysis of Refs. [4,5] and has been also directly seen with PRISMA+CLARA by means of cross coincidences (see later).

4 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 [17]. With heavy ions, interesting expectations are coming by looking at the Q-value distributions of the recently

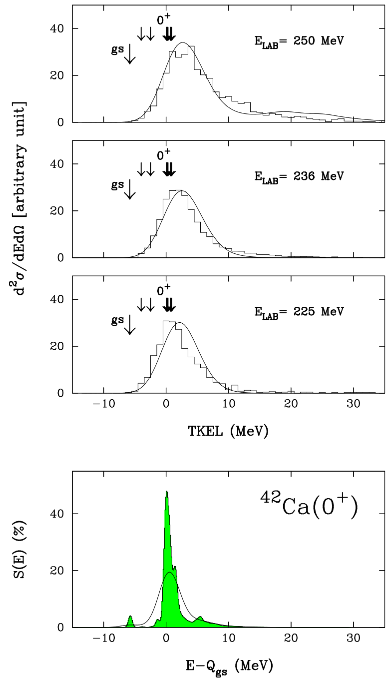

Fig. 3: Experimental (histograms) and theoretical (curves) total kinetic energy loss distributions of the two neutron pick-up channels at the indicated energies. The arrows correspond to the energies of 0^+ states in ^{42}Ca with an excitation energy lower than 7 MeV. Bottom panel shows the strength function S(E) from shell model calculations.

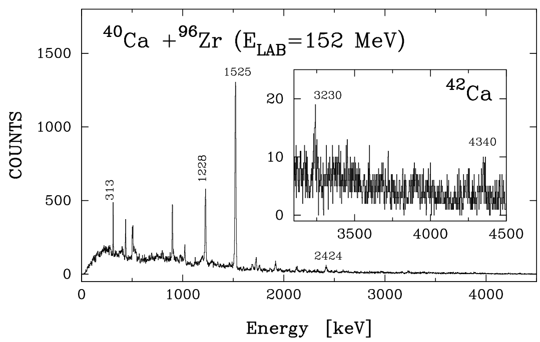

Fig. 4: γ-ray spectrum with expanded region in inlet for ^{42}Ca obtained in the ^{40}Ca+^{96}Zr reaction

measured ^{40}Ca+^{208}Pb reaction [18]. Fig. 3 shows the TKEL distributions at three bombarding energies for the two-neutron pick-up channel in comparison with calculations. As can be appreciated, the two neutron pick-up channel displays at all measured energies a well defined maximum, which, within the energy resolution of the experiment, is consistent with a dominant population, not of the ground state of ^{42}Ca, but of states with an excitation energy at around 6 MeV. The inspection of this population for the $+2n$ channel tells us that the maximum of the distributions correspond to the transfer of two neutrons in the $p_{3/2}$ orbital, we remind that the single particle form-factors for the $p_{3/2}$ orbital is much larger than the one for the $f_{7/2}$ orbital that constitutes the main configuration of the ground state of ^{42}Ca. The $(p_{3/2})^2$ configuration corresponds to the main component of the excited 0^+ states at around 5.8 MeV of excitation energy that were interpreted as multi (additional and removal) pair-phonon states [17]. The strong concentration of strength near 6 MeV of peculiar 0^+ states for ^{42}Ca (they must contain the $(p_{3/2})^2$ configuration) is clearly visible in the bottom part of Fig.2, where the strength distribution S(E) coming from large scale shell model calculations is shown. These results open, at least in our expectation, the possibility to study multi pair-phonon excitations.

The PRISMA+CLARA set-up should allow the observation of the decay pattern of the populated 0^+ states. In Fig. 4 we show the γ-spectrum for ^{42}Ca obtained in the reaction ^{40}Ca+^{96}Zr [9]. 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 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.

5 From quasi-elastic to deep-inelastic regime

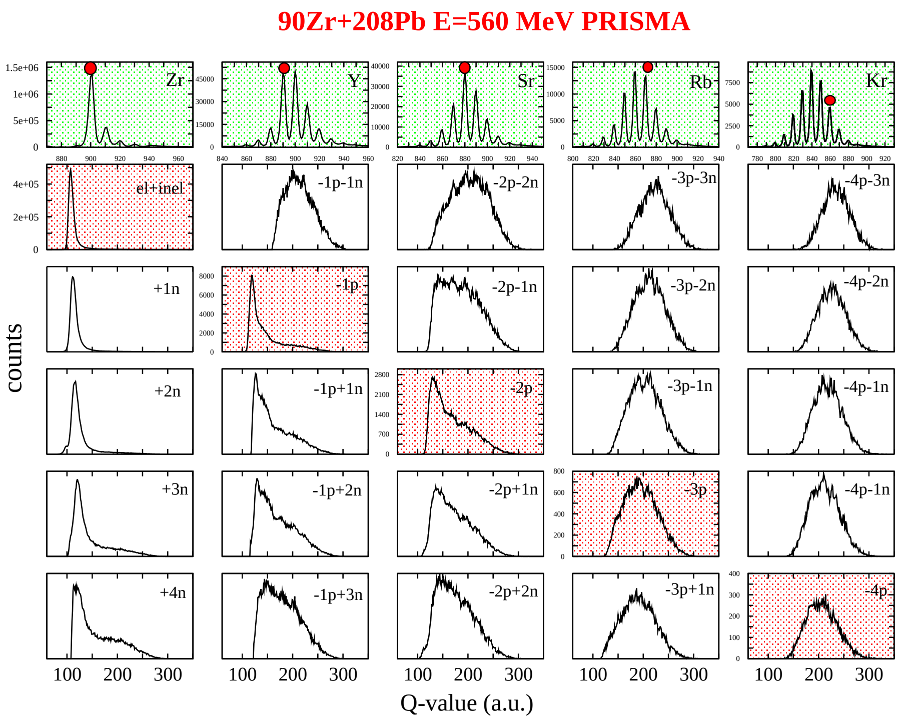

Fig. 5: TKEL spectra obtained in the reaction ^{90}Zr+^{208}Pb for the indicated transfer channels. In the top row are shown the mass distribution associated to the different nuclear charges, while the circles indicate the specific masses corresponding to the spectra displayed along the upper-left/lower-right diagonal. The centroid of the elastic+inelastic channel corresponds to Q=0. The scale of the Q-value axis is 1 MeV/channel.

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. 5 I show the TKEL spectra obtained in the ^{90}Zr+^{208}Pb reaction for different transfer channels. One can follow the evolution pattern as function of the number of transferred neutrons and protons. For instance, 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. I 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 decribed. 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. The importance of neutron evaporation in the modification of the final yield distribution was outlined in inclusive measurements [4, 5]. These effects can be directly seen with PRISMA+CLARA. 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. An example is given in Fig. 6 for the for the $-2p+2n$ channel populated in the ^{40}Ca+^{96}Zr reaction [9]. About 60$\%$ of the yield corresponds to the primary ^{96}Mo, while the rest is equally shared between isotopes corresponding to the evaporation of one and two neutrons. In general,

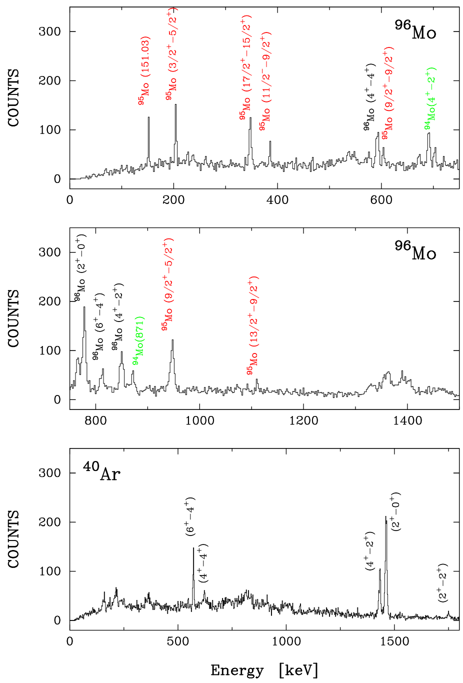

Fig. 6: γ spectra for the $-2p+2n$ channel in the reaction ^{40}Ca+^{96}Zr Doppler corrected for the heavy (top two frames) and light fragments (bottom frame). To have a better identification of the different γ lines for the heavy fragment we used an expanded energy scale.

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.

6 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 [2,3]. 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. To set the frame, one can write the transfer cross section as :

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

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 and $e^{i\omega_{if}}$ defining the Q-value window, 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 [19]. This fact should provide a simpler analysis of the data. From

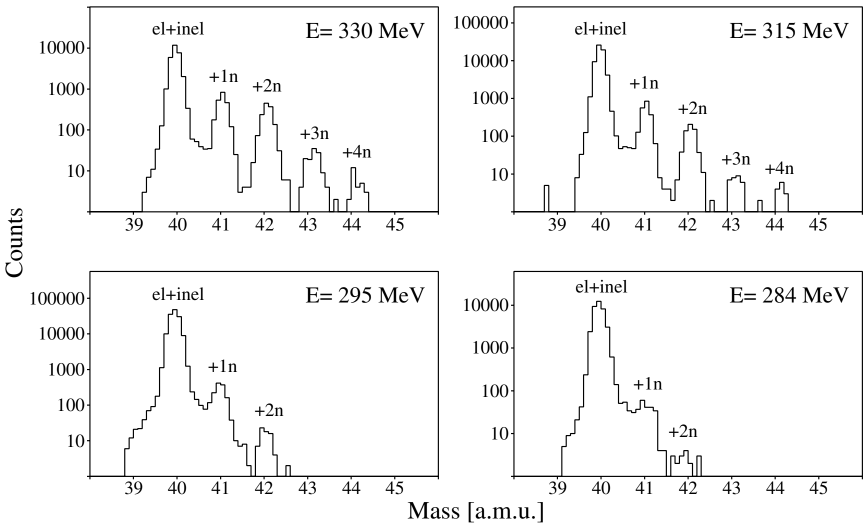

Fig. 7: Mass distributions for pure neutron transfer channels obtained in the reaction ^{94}Zr+^{40}Ca at the indicated bombarding energies. Ca-like recoils have been detected at θ_{lab}=20° with the PRISMA spectrometer.

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 $\theta_{cm} \simeq 180°$. 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 reactions ^{94,96}Zr+^{40}Ca at different bombarding energies below the Coulomb barrier, 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 previosuly measured with high precision [20] and a complete set of data for both multinucleon transfer and fusion reactions would provide an excellent basis for coupled channel calculations.

In Fig. 7 I show the mass spectra for pure neutron transfer channels in the system ^{94}Zr+^{40}Ca obtained after trajectory reconstruction at four bombarding energies. While at the higher energies one observes the populations of up to four nucleon transfer, at the lower energies (below the Coulomb barrier) only one and two 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 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 vs. one nucleon transfer should provide information on nucleon-nucleon correlation effects.

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