Recent Achievements in Multinucleon Transfer Reaction Studies at LNL

Introduction

What makes the field of nuclear reactions with heavy-ions so rich is the fact that the nucleus presents both the degrees of freedom associated with the single particle motion and those associated with the strong surface vibrations and rotations. In the low energy regime (close to the Coulomb barrier) it is the interplay of these two kinds of degrees of freedom that governs the evolution of the reaction from the quasi-elastic to the more complex deep-inelastic and fusion regimes. The quasi-elastic reactions, where few quanta are exhanged between target and projectile, constitue the most important tools for nuclear structure and reaction dynamics studies [1]. From the stripping and pick-up of neutrons and protons one can deduce informations about the shell structure close to the Fermi surface (one-particle transfer) of the two reactants or one can study nuclear correlations in the nuclear medium (multi-nucleon transfer reactions) [2–4]. Among these correlations of particular importance are the pairing one, that is, the ability of two nucleons to form a pair with zero angular momentum [1,2].

Extensive work using different heavy ion reactions has been performed during last few years with the time-of-flight magnetic spectrometer PISOLO, installed at the Laboratori Nazionali di Legnaro (LNL) [5]. The variety of channels that could be observed in several experiments allowed to follow in a systematic way the population pattern of the reaction products in the Z-A plane [6,7]. Parallel to this experimental work, semi-classical models have been implemented [8,9] that are able to treat quasi-elastic and deep-inelastic processes in terms of few and well-known degrees of freedom and that allow a quantitative comparison with the experimental observables.

Multinucleon transfer reactions constitute also a valuable tool to populate neutron-rich isotopes, at least in specific mass regions [10]. The study of the lowest excited levels of neutron-rich nuclei is an area of increasing interest for the verification of the predicted changes of the shell structure and of the nucleon-nucleon correlations far from the β-stability valley. A very powerful technique for these studies is constituted by the coupling of large gamma arrays detectors with the new generation of large solid angle spectrometers. At LNL the PRISMA heavy-ion magnetic spectrometer [11] coupled to CLARA [12] recently entered into operation.

Results from Inclusive Measurements with PISOLO

From the comparison between one and two particle transfer processes one can already learn a lot on the interplay between single-nucleon and pair-transfer modes, but it is only when several number of nucleons are transferred that one has a better view on how the mechanism evolves. An example of a complete measurement performed with PISOLO is that for the ^{58}Ni+^{208}Pb system [7]. The experimental total angle and Q-value integrated cross-sections for pure neutron pick-up and pure proton stripping channels are reported in Figure 1 in comparison with the calculations performed within the semiclassical Complex WKB (CWKB) model (see Ref. [7] and references therein for details).

The experimental data show, for neutrons, a quite regular drop of the cross-sections as a function of the number of transferred nucleons, indicating that the transfer mechanism is likely to proceed as a sequence of independent single-particle modes. Similar results have been obtained at Argonne [13]. With the dotted line in Figure 1 we show the calculations made treating the transfer in a successive approximation and considering all the transitions as independent. A good agreement with the data is obtained for all pure neutrons transfer channels and for the stripping of one proton. However the calculation misses the massive proton transfer channels underpredicting the two-proton stripping by an order of magnitude. The discrepancies indicate that the theory should incorporate more complex transfer degrees of freedom. By adding to the reaction mechanism the transfer of correlated pairs of protons and neutrons, in the macroscopic approximation, and fixing the strength of the formfactors to reproduce the pure −2p channel, one sees (dashed line) that the predictions for all other charge transfer channels are much better whereas no appreciable modifications are visible for the neutron transfer channels (dotted and dashed lines almost overlap with the full line in the right panel and are not shown). Because the pairing interaction has the same strength for neutrons and protons we kept the same form factors for the +2n and −2p channels. The contribution of the pair mode for neutron is negligible due to the fact that its effect is masked by the successive mechanism; notice, in fact, that the cross-section for the +1n channel is almost a factor ten larger than the one of −1p channel. In multi-nucleon transfer channels large energy losses are reached, therefore the final yield can be considerably altered by evaporation, mostly neutrons. Including these evaporation effects a much better prediction is obtained for the final cross-sections, as shown by the full line in Figure 1. The calculation includes the transitions among all the single particle levels of target and projectile of a full shell below the Fermi surface and of all the ones above. To see if this choice of the shell model space is adeguate for these reactions we look at the Total Kinetic Energy Loss (TKEL) spectra. In Figure 2 are shown TKEL distributions for the system ^{62}Ni + ^{206}Pb, measured [6] at three bombarding energies, for an angle close to the grazing one.

Figure 2 shows that only the +1n and +2n channels have the main population concentrated in a narrow low energy region (close to the ground-ground state transition), and the theory gives a very good description, whereas for more massive transfer channels the populations widen and shift toward more negative Q-values developing tails that increase with the number of transferred neutrons. This may indicate that, even for this system where all neutron transfer pick-up channels are at optimun Q-value, the "cold" transfers (associated with low excitation energy) are hindered by processes that drive the population toward high excitation energy. By looking at the angular distributions of the same channels one sees that they display a bell-shaped form (underlying the grazing character of the reaction) with a width that increases with the number of transferred particles in particular in the forward direction.

These observations, both in the TKEL and angular distributions, indicate the relevance of the surface degrees of freedom. It is, in fact, the surface dynamics, governed by the low lying modes, that allows the two ions to stay in close contact for longer times and thus to build up a "neck" between the two colliding partners.

Quite interesting expectations are coming by looking at the Q-value distributions of the ^{40}Ca+^{208}Pb reaction [14]. Figure 3 shows the TKEL distributions at three bombarding energies for the two-neutron pick-up channel in comparison with CWKB 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. From the theoretical calculations one can see how the different single particle levels are populated in the reaction. 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; note that the single particle form-factors for the $p_{3/2}$ orbital are 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 5.4 MeV of excitation energy that were interpreted as multi (additional and removal) pair-phonon states [2]. These results open, at least in our expectation, the possibility to study multipair-phonon excitations. The strong concentration of strength near 6 MeV

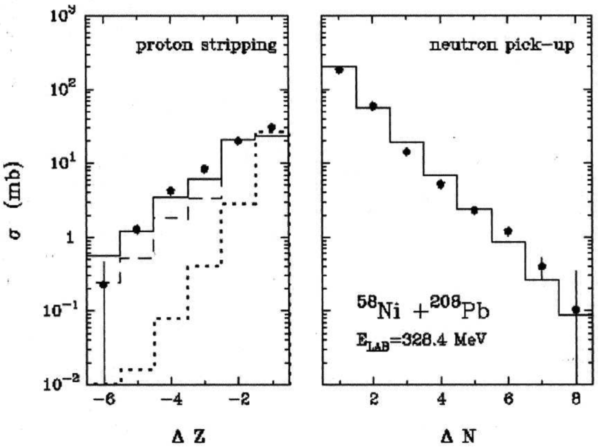

Figure 1. *Total cross-sections for pure proton stripping (left side) and pure neutron pick-up (right side) channels for the indicated reaction. The lines are the CWKB calculation.*

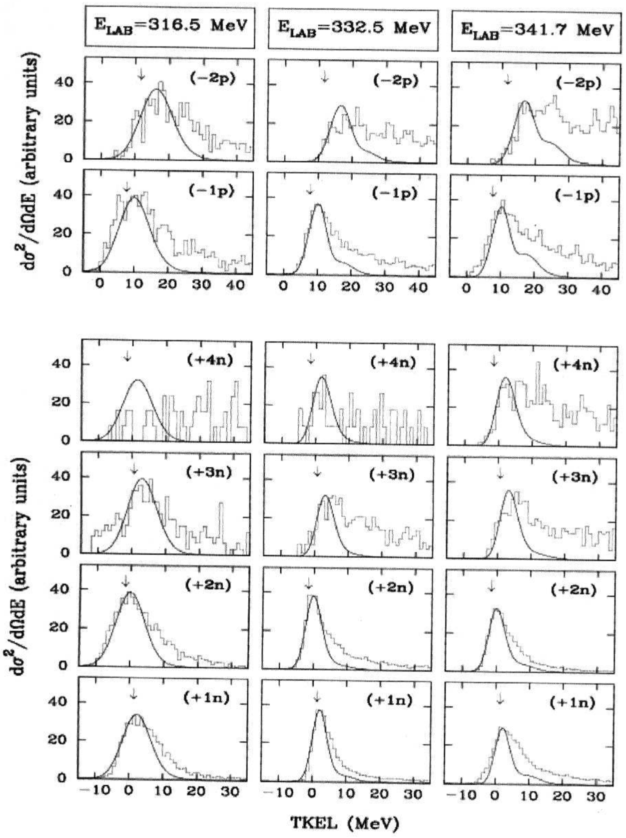

Figure 2. *Experimental (histograms) and theoretical (lines) total kinetic energy loss (TKEL) distributions for pure neutron pick-up and proton stripping channels in the reaction $^{62}Ni + ^{206}Pb$. The ground-ground state Q-values are indicated by the down arrows (see Ref. [6] for details).*

of peculiar 0^+ states for ^{42}Ca (they must contain the $(p_{3/2})^2$ configuration) is clearly visible in the bottom part of Figure 3, where the strength distribution S(E) coming from large scale shell model calculations is shown [14].

Measurements with the PRISMA Large Solid Angle Spectrometer

From the discussion in the last section it is clear that for the definite assigment of the states at around 6 MeV in ^{42}Ca it would be important to distinguish the population to specific nuclear states and to determine both their strength distribution and decay pattern. This, in fact, carries information on the wavefunctions of the populated levels and on the pairing correlation [1]. Experiments in this direction must exploit the full capability of spectrometers with solid angles much larger than the conventional ones, and with A, Z, and energy resolutions sufficient to deal also with heavy mass ions. This is now possible with the PRISMA spectrometer [11] designed for the A = 100–200, E = 5–10 MeV/amu heavy-ion beams of the accelerator complex of LNL. First experiments on heavy-ions grazing collisions have been already performed with beams in the A = 40–90 range. One of the present interests are nuclear structure studies of neutron-rich nuclei, populated at relatively high angular momentum, by means of binary reactions. These studies are performed by combining PRISMA with the CLARA gamma-array [12], recently installed close to the target point and consisting of an array of 24 Clover detectors from the Euroball collaboration. With stable beams and at the energies and intensities typical of tandem accelerators, one can presently reach regions moderately far from β-stability (on average 3–5 nucleons from the last stable isotope), but one can investigate nuclei through the entire nuclear chart, provided suitable projectile/targets are chosen.

An exploratory run with PRISMA+CLARA has been very recently done by using the reaction $^{90}Zr + ^{208}Pb$ with the main aim of looking at the yield production of specific Q-value ranges in the Zr and Sr

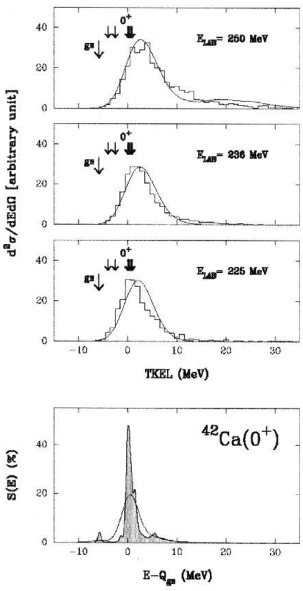

Figure 3. *Experimental (histograms) and theoretical (curves) total kinetic energy loss distributions of the two neutron pick-up channels at the indicated energies. The arrows correspond to the energies of 0^+ states in ^{42}Ca with an excitation energy lower than 7 MeV. Bottom panel shows the strength function S(E) from shell model calculations (see Ref. [14] for details).*

isotopes close to the expected region where pair vibrational modes may be excited. The spectrum in Figure 4 shows an example of the obtained mass resolution in such a reaction at E_{lab} = 560 MeV. One observes events corresponding to the pick-up as well as stripping of neutrons. The right side (left side) are the spectra obtained with (without) gamma coincidences. One observes different relative yields in mass spectra for each isotope, due to the different gamma multiplicities for the various multinucleon transfer channels populated in the reaction. In the bottom part is shown, as an example, the coincident gamma spectrum for ^{90}Zr, obtained after Doppler correction for the projectile-like nuclei selected by the spectrometer. In general, the Zr isotopes span a range from spherical to highly deformed shapes and it would be therefore interesting to investigate in detail the change of the population strength and decay pattern properties of specific levels populated via multinucleon transfer mechanism.

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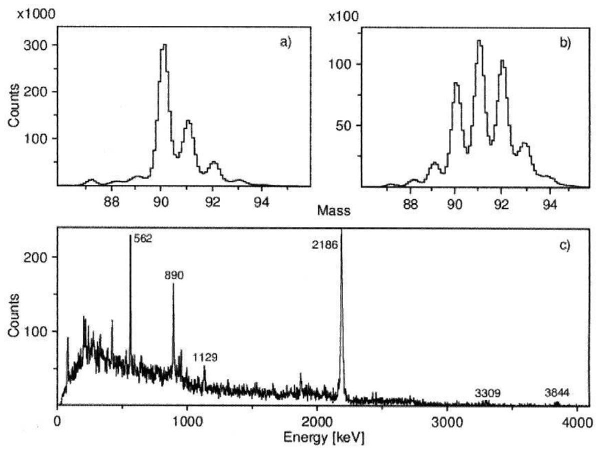

Figure 4. *Panels (a) and (b) : mass distributions for Zr isotopes obtained in the $^{90}Zr + ^{208}Pb$ reaction at E_{lab} = 560 MeV and at $\theta_{lab} = 54^0$, without (a) and with (b) gamma coincidences. Panel (c): single gamma spectrum of ^{90}Zr. The peak at 2186 keV corresponds to the lowest $2^+ - 0^+$ transition.*

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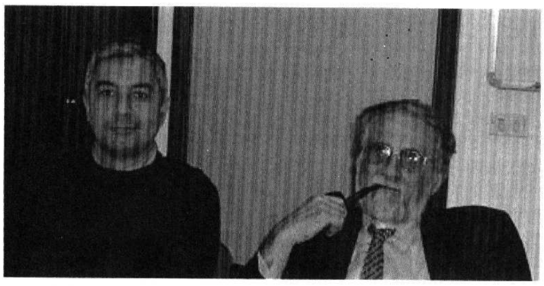

L. Corradi (left) and G. Pollarolo (right).

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