

Multinucleon Transfer Reactions Studied with Magnetic Spectrometers

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We discuss some of the main features emerging from recent studies on multinucleon transfer reactions at energies close to the Coulomb barrier. The possible effects of pair modes are analyzed in inclusive measurements of $^{58}\text{Ni} + ^{208}\text{Pb}$ and $^{40}\text{Ca} + ^{208}\text{Pb}$ systems. New possibilities offered by using the large solid angle spectrometer PRISMA are outlined.

§1. Introduction

Quasi-elastic and deep inelastic processes have been traditionally studied in different ways, both theoretically and experimentally.¹⁾ From the theoretical point of view, in the quasi-elastic regime (i.e. few transferred nucleons and small energy losses) one or, at most, two-nucleon transfer has been treated using DWBA or Coupled Channel codes, while in the deep inelastic regime (i.e. many transferred nucleons and large energy losses) stochastic, friction or diffusion models have been used. From the experimental point of view, nuclei produced in transfer reactions have been identified with good mass A , nuclear charge Z and energy resolutions for medium-light systems, but channel detection was limited to the transfer of very few nucleons. For medium-heavy systems, mainly studied in deep-inelastic processes, the transfer of several nucleons becomes available in the reaction but, at best, Z identification was possible without A or energy resolution.

It was not until very recently that, thanks to the development of efficient spectrometers, one could identify with high resolution multinucleon transfer channels populated in heavy-ion reactions up to the pick-up and stripping of several neutrons and protons.^{2),3)} Advances in theoretical calculations^{4),5)} allowed also to quantitatively study how degrees of freedom of different complexity act in the transfer process. This “transition” regime, where many nucleons are transferred and where shell effects still play a significant role in the dynamics, represents a window not well studied in its detail and where it is interesting to investigate the interplay between single nucleon and pair transfer modes and their dynamical effects as a function of energy loss, angular momentum and number of transferred nucleons. The understanding of these processes is important in view of future research to be done with radioactive beams,^{5),6)} since one expects for instance a very different behaviour of

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nucleon correlation effects for neutron-rich nuclei. Multinucleon transfer processes are also recognized to be a competitive tool for the production of neutron-rich nuclei, at least for certain mass regions.⁷⁾ In this contribution examples of recent studies performed with time-of-flight and magnetic spectrometers are discussed.

§2. Measurements with the time-of-flight spectrometer PISOLO

The time-of-flight magnetic spectrometer PISOLO,^{3),8)} installed at LNL, has been especially designed to combine a high efficiency ($\simeq 3$ msr) and high A and Z resolution ($\Delta A/A \simeq 1/100$ and $\Delta Z/Z \simeq 1/60$, respectively) for heavy ions with $A \leq 100$ produced in binary reactions at energies down to $\simeq 1$ MeV/amu. One of the main achievements of the studies performed with PISOLO was the unambiguous identification in several systems of channels corresponding to the pick-up of up to six-eight neutrons and the stripping of six-eight protons. The variety of channels which could be observed allowed to follow in a systematic way the population pattern of the reaction products in the Z - A plane.

2.1. Inclusive cross sections: the $^{58}\text{Ni}+^{208}\text{Pb}$ system

The $^{58}\text{Ni}+^{208}\text{Pb}$ system⁹⁾ has Q -value matching conditions close to optimum up to several neutron pick-up and proton stripping channels. It represents therefore a suitable case to investigate the mass and charge distributions of the multinucleon transfer products. A ^{58}Ni beam was accelerated onto a ^{208}Pb target at the energy of $E_{\text{LAB}} = 328.4$ MeV with the Tandem+ALPI booster of LNL. Light reaction products were identified with PISOLO, while the associated heavy partners were detected in kinematic coincidence using a transmission-type multiwire parallel-plate avalanche counter. The detection of the heavy partner (which will not be discussed here) gives important information on how the same transfer mechanism behaves in the production of high Z heavy nuclei.^{9)–11)}

In Fig. 1 are shown the total angle- and Q -value integrated cross sections for pure neutron pick-up and pure proton stripping channels. The experimental data show a quite regular drop of the cross sections as a function of the number of transferred nucleons, indicating that the transfer mechanism likely proceeds as a sequence of independent particle modes. The data are compared with calculations performed with the semiclassical Complex WKB (CWKB) model, described in Ref. 12). The model was first developed to deal with one-particle transfer and later generalised to compute cross sections of multi-nucleon transfer channels via a sequence of single nucleons and of pair modes. The model is well suited for the study of transfer reactions at Coulomb barrier energies and was already successfully used in the comparison with experimental data for various systems (see Refs. 3), 9) and references therein).

In the CWKB approximation the cross section for the transfer from the single-particle state $a_i \equiv (n_i, l_i, j_i)$ to the single-particle state $a_f \equiv (n_f, l_f, j_f)$, belonging

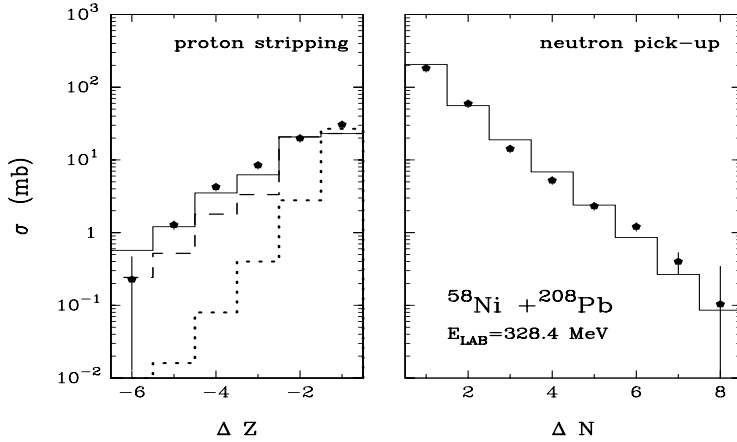


Fig. 1. Total cross sections for pure proton stripping (left side) and pure neutron pick-up (right side) channels. The dotted line is the CWKB calculation including single nucleon transfer modes. The dashed line represents the result with an additional two-proton pair mode and the solid line includes also the effect of nucleon evaporation from the primary fragments. For the pure neutron transfer no pair transfer was included and the cross section represented by the dashed and the dashed-dotted lines (not shown) are very close to the full line.

to different nuclei, may be written as

$$\left[\frac{d\sigma}{d\Omega} \right]_{a_f a_i} = V^2(a_i) U^2(a_f) \sum_{\lambda} \left(\frac{d\sigma}{d\Omega} \right)_{\lambda}, \quad (2.1)$$

where the sum has to be extended over all the allowed angular momentum transfer λ . The quantity $V^2(a_i)$ represents the probability that the single-particle orbital is occupied, while the quantity $U^2(a_f) = 1 - V^2(a_f)$ is the corresponding probability that the orbital is empty. V^2 and U^2 are directly related to the spectroscopic factors.

The transfer cross section for each λ transfer may be written as

$$\left(\frac{d\sigma}{d\Omega} \right)_{\lambda} = \frac{\kappa_f}{\kappa_i} \left| \sum_{\ell} \sum_{\mu} c_{\lambda\mu}^{a_f a_i}(\ell) f_{\ell}(\theta) \right|^2, \quad (2.2)$$

where κ_i and κ_f are the asymptotic wave numbers in the entrance and exit channel respectively, $c_{\lambda\mu}^{a_f a_i}(\ell)$ is the semiclassical amplitude for the transition from the initial state a_i to the final state a_f for the partial wave ℓ , and $f_{\ell}(\theta)$ is the elastic scattering amplitude for the same partial wave ℓ .

The transfer amplitude $c_{\lambda\mu}^{a_f a_i}(\ell)$, in first order Born approximation and in the low-recoil limit,^{(13), (14)} is given by

$$c_{\lambda\mu}^{a_f a_i}(\ell) = \sqrt{\frac{1}{4\pi\hbar^2}} D_{\mu 0}^{\lambda} \left(0, \frac{\pi}{2}, 0 \right) \int_{-\infty}^{+\infty} dt f_{\lambda}^{a_f a_i}(r(t)) e^{\frac{i}{\hbar}[(\Delta E - Q_{opt} + \Delta)t - \hbar\mu\phi(t)]}. \quad (2.3)$$

In the above expression $f_{\lambda}^{a_f a_i}(r(t))$ is the single particle formfactor for the transition from the single-particle state a_i to the single-particle state a_f , Q_{opt} is the optimum Q -value, and the quantity Δ takes into account the mismatch between the entrance and

exit channel trajectories. The time integral has to be performed along the classical trajectory associated to the partial wave ℓ . The semiclassical amplitudes $c_{\lambda\mu}^{a_f a_i}(\ell)$ are evaluated in the CWKB approximation by utilizing the single-particle formfactors of Refs. 13), 14) to which we refer for details. With the above expression of the transfer amplitude one can construct the probability to generate a given charge transfer ΔZ , mass transfer ΔM , excitation energy and angular momentum of light and heavy partners produced in multinucleon transfer reactions, according to a Montecarlo procedure.⁹⁾

With the dotted line of Fig. 1 we show the calculations made treating the transfer in a successive approximation considering all the transitions as independent. A good agreement between data and theory is obtained for the case of pure neutrons and for channels involving the stripping of one proton. However, as more protons are transferred the calculations are not able to follow the trend of the data. The discrepancies indicate that degrees of freedom beyond single-particle transfer modes have to be incorporated in the theory, or that more complex processes, i.e. deep inelastic components, play an important role. A new degree of freedom was then added into theory, namely the transfer of a pair of protons. Fixing the strength of the macroscopic formfactor¹⁵⁾ to reproduce the pure $-2p$ channel we obtain the results shown with the dashed line. We see that once the yield of the $-2p$ channel is reproduced, the predictions for the other charge transfer channels are also much better indicating that the proton pair mode may be an important degree of freedom in the transfer process. Why this mode seems to be required only for proton channels is presently not clear. However, its treatment is only at a phenomenological level due to the well known difficulties to relate microscopically its strength to the pair correlations in target and in projectile (both enter in the definition of the form factor).

In the experimental spectra of the multinucleon transfer channels large energy losses show-up, therefore the final yield can be considerably altered by evaporation. To estimate the effect of the evaporation on the fragment distribution, we first extracted the excitation energy and final angular momenta of the different light (and heavy) products from the CWKB model. These values, for each Z and A , were then used as inputs in the evaporation code PACE2,¹⁶⁾ that provides the final mass and charge partitions computing the evaporation of nucleons according to the statistical model. Using the default parameters of PACE2, the final cross sections obtained for the light fragments are shown as a full line in Fig. 1.

2.2. *Q-value distributions: the $^{40}\text{Ca}+^{208}\text{Pb}$ system*

Further interesting inputs for understanding the role played by pair mode degrees of freedom in the transfer process are coming from the study of $^{40}\text{Ca}+^{208}\text{Pb}$,¹⁷⁾ where both projectile and target are double closed shell nuclei and therefore provide an excellent opportunity for a quantitative comparison with theoretical model. A ^{40}Ca beam was accelerated onto a ^{208}Pb target at several bombarding energies close to the Coulomb barrier, i.e. $E_{\text{lab}} = 250, 236$ and 225 MeV, and detection of light products, similarly to the previous experiment, was done with PISOLO. Taking into account the intrinsic resolution of the detector, target thickness, and the kinematic energy

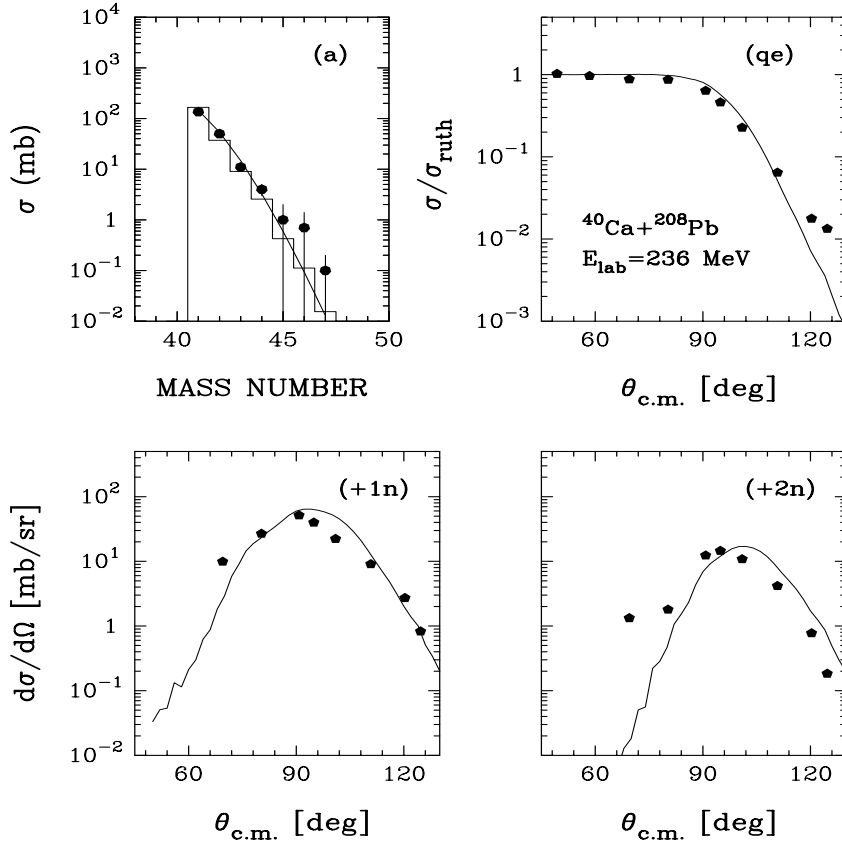


Fig. 2. In (a) the angle and Q -value integrated cross sections of the pure neutron pick-up channels for the $^{40}\text{Ca}+^{208}\text{Pb}$ reaction at $E_{\text{lab}} = 236$ MeV (dots) are shown as a function of the mass number together with the theoretical (CWKB) prediction (histogram). The curve corresponds to a poissonian distribution with an average number of transferred particles $\langle n \rangle = 1.1$. In the other frames the Q -value integrated angular distributions for the quasi-elastic (qe), one-neutron (+1n) and two-neutron (+2n) pick-up channels (dots) are shown together with the theoretical calculation (curves).

shift the obtained energy resolution was $\simeq 2$ MeV. We focus the discussion on pure neutron transfer channels. In Fig. 2 we show the experimental total cross sections and the differential cross sections for the quasi-elastic and +1n and +2n channels, at $E_{\text{lab}} = 236$ MeV, together with the CWKB theory. Again, the integrated cross sections decrease smoothly as a function of the number of transferred nucleons, without any clear odd-even staggering, in agreement with a poissonian distribution, with an average number of transferred neutrons $\langle n \rangle = 1.1$. From the observed behavior of the inclusive total cross sections alone it is difficult to draw unambiguous conclusions on the role played by a pair transfer mode.

Figure 3 shows the total kinetic energy loss distributions at the three bombarding energies for the two neutron pick-up channel together with the CWKB calculations. As can be appreciated, the two neutron pick-up channel displays a well defined maximum which, within the present energy resolution, is consistent with a dominant

population, not of the ground state of ^{42}Ca , but of the excitation region around 6 MeV (see below and Refs. 18), 19)). All measured energies show the same behavior and as the beam energy decreases the distributions become narrower, the large energy loss tail tends to disappear, and the centroids slightly shift to lower energies reflecting the energy dependence of the optimum Q -value. Both features are well reproduced by the theoretical calculations indicating that the used single particle levels cover the full Q -value ranges spanned by the reaction.

We remind that systematic studies of (p, t) and (t, p) reactions lead to identify the calcium region as the only known where the cross sections for the population of the excited 0^+ states are larger than the ground state. In most Ca isotopes the excited 0^+ strength is concentrated in one state only. Those states have been recognised as multi (additional and removal) pair-phonon states.²⁰⁾ Nuclear structure and reaction dynamics studies attribute this behavior to the influence of the $p_{3/2}$ orbital that gives a much larger contribution to the two-nucleon transfer cross section than the $f_{7/2}$ orbital, which dominates the ground state wave function. Referring to Fig. 3, the final population of the single particle levels used in the CWKB theory suggests that the maxima are essentially due to two neutrons in the $p_{3/2}$ orbital, i.e. to the excited 0^+ states at around 6 MeV of excitation energy that were interpreted as corresponding to the pair vibrational mode. If so, these results show that, at least in suitable cases, one can selectively populate specific Q -value ranges even in heavy-ion collisions, opening the possibility to study multi pair-phonon excitations.

In order to pursue these studies in a more quantitative way it would be important to distinguish the population to specific nuclear states and to determine the decay pattern of the populated levels since this carries information on their wavefunction components and therefore also on the pairing correlation. Experiments in this direction must exploit the full capability of spectrometers with solid angles much higher than the conventional ones, and with A , Z , and energy resolutions sufficient to deal also with heavier mass ions.

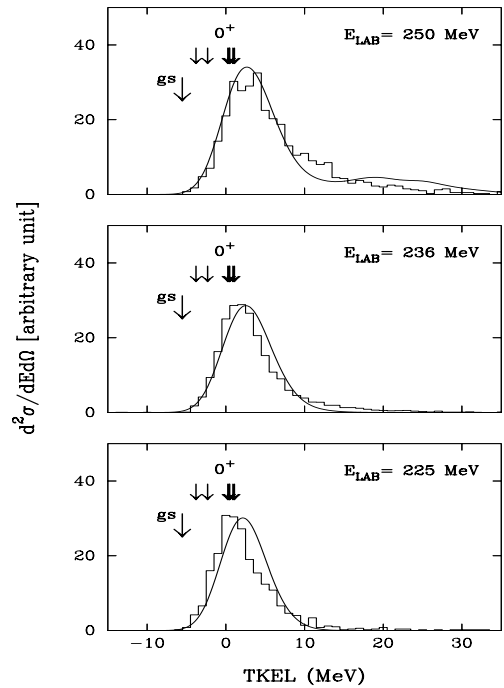


Fig. 3. Experimental (histograms) and theoretical (curves) total kinetic energy loss distributions of the two neutron pick-up channel at the indicated energies. The arrows correspond to the energies of 0^+ states in ^{42}Ca with an excitation energy lower than 7 MeV. The group of states at 5.87 (collecting most of the strength), 6.02, 6.51 and 6.70 MeV were strongly populated in (t, p) reactions.^{18), 19)}

§3. Measurements with the magnetic spectrometer PRISMA

PRISMA is a new magnetic spectrometer²¹⁾ recently installed at LNL and designed for the $A = 100\text{--}200$, $E = 5\text{--}10$ MeV/amu heavy-ion beams of the accelerator complex of LNL. Briefly, PRISMA consists of a quadrupole singlet and a dipole. Its main features are large solid angle 80 msr, wide momentum acceptance $\pm 10\%$, mass resolution $1/300$ via time-of-flight and energy resolution up to $1/1000$. The large segmented ionization chamber (IC) at the focal plane has a multinode structure providing multiple ΔE and E_{tot} signals. A multiwire parallel plate detector array is placed upstream of the IC, consisting of 10 equal detector sections, and providing X,Y and timing signals. The entrance detector, installed between the target and the quadrupole magnet, is based on Micro-Channel Plates, and gives timing and X,Y position signals.

3.1. First results

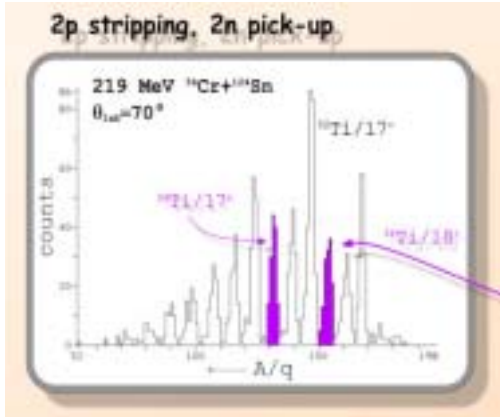


Fig. 4. A/q spectrum of titanium isotopes obtained in the indicated reaction. The shaded peaks correspond to ^{54}Ti nuclei ($-2p+2n$ channel) with two different atomic charge states q selected by the spectrometer.

tained by selecting $Z = 22$ events in the IC, and various titanium isotopes are identified.

PRISMA with its characteristics offers interesting possibilities to study the population of multi-pair phonon states in heavy-ion collisions. Examples of suitable candidates, besides the region around Ca isotopes discussed in the previous section, are the nuclei in the Sr-Zr region, which can be populated in reactions like $^{90,96}\text{Zr} + ^{208}\text{Pb}$. Zr isotopes, in particular, span a range from spherical to highly deformed shapes and it would be therefore interesting to investigate into detail the change of the population strength and decay pattern properties of specific levels populated via multinucleon transfer mechanism. These difficult experiments will

The first experiments on heavy-ions grazing collisions were performed recently. The goals of the experiments were to investigate the population of neutron-rich nuclei in the $A = 50\text{--}60$ mass region by means of multinucleon transfer reactions, and to study the dynamics of such transfer processes. We used ^{54}Cr , ^{56}Fe and ^{64}Ni projectiles on neutron-rich targets like ^{124}Sn , at incident energies close to the Coulomb barrier. Angular distributions of the transfer reactions and of quasi-elastic scattering were measured in an angular range around the grazing angle, in order to identify multinucleon transfer channels populated with small cross sections. Very good A and Z resolutions were reached ($\Delta A/A = 1/280$ routinely). The spectrum in Fig. 4 is ob-

benefit from the use of the large γ -array CLARA,²²⁾ recently installed close to the target point and consisting of an array of 25 Clover detectors from the Euroball collaboration. With the PRISMA+CLARA set-up, more in general, one can study the nuclear structure of moderately neutron-rich nuclei, populated at relatively high angular momentum, by means of binary reactions.

§4. Summary

In recent inclusive studies of $^{58}\text{Ni}+^{208}\text{Pb}$ and $^{40}\text{Ca}+^{208}\text{Pb}$ multinucleon transfer reactions important features of the transfer process were identified. By comparing data with CWKB calculations we found a different behaviour of proton vs neutron transfer, which is presently not understood. For protons theory calculates well the total cross sections including degrees of freedom of increasing complexity, however it is still a challenge to compute the pair mode on a microscopic basis. A selective population of Q -values in ^{42}Ca has been identified and it is suggested to be due to the pair mode excitations. Multinucleon transfer reactions, and in particular the study of pair vibrational/rotational modes, will benefit from the use of the high resolution and high efficiency magnetic spectrometer PRISMA, coupled to the CLARA γ array.

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