PRAMANA — journal of physics
Vol. 53, No. 3
September 1999
pp. 473–481

Multinucleon transfer reactions

G POLLAROLO
Dipartimento di Fisica Teorica, Universitá di Torino and INFN Sezione di Torino,
Via Pietro Giuria 1, 10125 Torino, Italy

Abstract. In this talk I will discuss transfer reactions between heavy ions with special emphasis to multinucleon transfer. I will use a semi-classical model that incorporates, in an independent description, both inelastic excitation to collective states and one-particle transfer channels. The importance of evaporation in determining the isotope distribution of the final yields of the reaction will be discussed.

Keywords. Transfer; multi-nucleon; neutron evaporation.

PACS No. 25.70.Jj

1. Introduction

The outstanding characteristic of heavy ion collisions at energy close, and even below, the Coulomb barrier is the interplay between several channels (or if you prefer several degrees of freedom). The coupling among these degrees of freedom results in important multi-step contributions to some specific channels. The number of channels (degrees of freedom) involved in a given situation depend upon the chosen representation. We invoke the standard degrees of freedom corresponding to the separated ions, viz., collective variables and single particle states. In this way we can calculate the yields for those channels that can be accessed by the experiments.

One has to keep in mind that in special situations the number of channels one has to include in the calculation may be very large so that they cannot be treated explicitly. In such a situation a macroscopic description that involves the degrees of freedom of the combined system (neck, neutron flow,...) may be more appropriate. One has however to keep in mind that in this macroscopic description, one misses the asymptotic channels so that one can only describe inclusive experiments.

The presence of multi-step contributions to specific reaction channel shows itself in several cases: elastic scattering via the polarization potential, inelastic scattering via the energy dependence of the form-factors, fusion enhancement, multiple particle transfer. In this talk I will be mostly concerned with single particle degrees of freedom, in particular I will discuss particle transfer reactions with special attention to the multinucleon transfer channels. In doing so I will make use of a model GRAZING [1–4] developed, over many years, at the Niels Bohr Institute (Copenhagen) and that has been used very successfully in the description of grazing reactions. In particular one has been able to elucidate the importance of one-particle transfer channels in the imaginary part of the optical potential [5,6] and also in the polarization potential [7].

This talk will be organized as follows, I will introduce first a very brief summary of the theoretical concepts avoiding all the technical details but just listing the different ingredients that define it, then I will concentrate on the comparison with the data. These were taken at the Laboratori Nazionali di Legnaro (Italy), with a new time-of-flight spectrometer with good mass and charge resolution that allowed the identification of the individual nuclei produced in the reactions. And then I will discuss the importance of the evaporation in determining the final yields of the different isotopes produced in the collision.

2. The theory

In the semiclassical description of grazing reactions one uses a basis that is a product of the eigenstates of the two separated ions. The relative motion is treated classically and the time dependence amplitude c_β of the product eigenstates $\psi_\beta = \psi^b(\xi_b)\psi^B(\xi_B)$ is given by the following system of coupled equations

$$i\hbar\dot{c}_\beta(t) = \sum_\gamma \langle\beta|(V_\gamma - U_\gamma)|\gamma\rangle c_\gamma(t)\mathrm{e}^{i(E_\beta - E_\gamma)t/\hbar} \tag{1}$$

that has to be solved with the initial condition $c_\beta = \delta_{\alpha\beta}$, α being the entrance channels. The potential U_γ is the expectation value of the interaction V_γ (i.e. the folding potential in the appropriate channel) and determines the classical trajectory along which the two ions move (for more details cfr. [8]). The quantity $Q_{\beta\gamma} = E_\beta - E_\gamma$ defines the Q-value of the transition. To calculate the physical observable one has to solve the above system of coupled equations for each impact parameter ρ and to use the familiar formulae of the semiclassical approximation.

In an heavy ion reaction beside the excitation of few inelastic collective modes one should include also the transfer channels namely the stripping and pick-up of neutrons and protons. Since we want to deal with the transfer of many nucleons we must rely on multistep transition. In this case the number of channels becomes immediately very large so that the direct solution of eq. (1) becomes impossible. We must thus resort to a simplified solution.

We are interested, for all impact parameters, to know the probability

$$P(E_a^*, M_a, N_a, Z_a, \cdots) = \langle\bar{\Psi}(t)|(\delta(E_a - \hat{H}_a)\delta(E_a - \hat{H}_a), \cdots|\Psi(t)\rangle \tag{2}$$

to have a final state with products of mass $A_i = N_i + Z_i$, excitation energy E_i^* and angular momentum M_i $(i \equiv a, A)$. Following refs [1–3] the calculation of the above probability is done by introducing the characteristic function

$$Z(\beta_a, \beta_A, \cdots) = \langle\bar{\Psi}(t)|\mathrm{e}^{i(\hat{H}_a\beta_a + \hat{H}_A\beta_A)+\cdots}|\Psi(t)\rangle \tag{3}$$

once this function is calculated the above probabilities are obtained via Fourier transforms.

The single particle operators that enter in the definition of the probability introduced above are the intrinsic Hamiltonians $\hat{H}_i$, the intrinsic angular momentum $\hat{M}_i$ the numbers operators $\hat{N}_i$ for neutrons and $\hat{Z}_i$ protons. In term of the usual creation operators, for the projectile system, they are defined

$$\hat{H}_a = \sum_{i=\pi,\nu} \epsilon_i a_i^\dagger a_i + \sum_n \hbar\omega_n \alpha_n^\dagger \alpha_n,$$
$$\hat{M}_a = \sum_{i=\pi,\nu} m_i a_i^\dagger a_i + \sum_n \mu_n \alpha_n^\dagger \alpha_n,$$
$$\hat{N}_a = \sum_{i=\nu} a_i^\dagger a_i,$$
$$\hat{Z}_a = \sum_{i=\pi} a_i^\dagger a_i, \tag{4}$$

with i we have indicated the single-particle quantum number of energy ϵ_i and with n the quantum number of the collective modes of energy $\hbar\omega_n$. Similar expressions hold for the target system.

The quantity $|\Psi(t)\rangle$ is the time dependent state vector of the system. It may be calculated from the expression:

$$|\Psi(t)\rangle = \mathcal{T} \exp\left\{ -\frac{1}{\hbar}\int_{-\infty}^{t} \tilde{V}^{\alpha}(t')\mathrm{d}t' \right\}|0\rangle, \tag{5}$$

where $|0\rangle$ is the entrance channel, $\mathcal{T}$ is the time ordering operator and $\tilde{V}^{\alpha}(t)$ is the coupling term written in the interaction representation.

To be able to calculate the characteristic function I still have to introduce the interaction that governs the exchange of mass and charge between the two ions and the exchange of energy and angular momentum from the relative motion to the intrinsic states. This interaction term has two components, one responsible for the exchange of mass and charge and a second responsible for the excitation of the collective states. We thus write

$$\hat{V}_\alpha = \hat{V}_{\mathrm{tr}} + \hat{V}_{\mathrm{in}}, \tag{6}$$

where

$$\hat{V}_{\mathrm{in}} = \sum_n f^n(\mathbf{r})\left(\alpha_n^\dagger \mathrm{e}^{i\omega_n t} + \alpha_n \mathrm{e}^{-i\omega_n t}\right) + \ (\mathrm{target\ \ system}). \tag{7}$$

$f^n(\mathbf{r})$ is the collective form factors, proportional to the derivative of the ion–ion potential, for the excitation of the collective state with energy $\hbar\omega_n$ and quantum number n. The interaction responsible for the transfer of particles may be written as

$$\hat{V}_{\mathrm{tr}} = \sum_{i,j}\left[f^{ij}(\mathbf{r}) a_j^\dagger a_i \mathrm{e}^{i/\hbar((\epsilon_j-\epsilon_i)t)} + f^{ji}(\mathbf{r}) a_i^\dagger a_j \mathrm{e}^{i/\hbar(\epsilon_i-\epsilon_j)t}\right], \tag{8}$$

where $f^{ij}(\mathbf{r})$ are the single particle form factors for stripping from the single particle state i in the projectile to the single particle j in the target and where $f^{ji}(\mathbf{r})$ are the corresponding form factors for pick-up reactions [5,8]. Of course they are function of the relative distance $\mathbf{r}$ and of the momentum transfer. The sum has to be extended over all neutrons and protons single particle states.

With the definition of all the operators, one is in a condition, with standard technique, to calculate the characteristic function and thus the probabilities of eq. (2), for more details cfr. [2, 3].

Summarizing, in this model the collision between two heavy ions has been reduced to the study of the redistribution in time of nucleons among two single particle density distributions that move along classical trajectories. This approximation is justified, a posteriori, by the fact that the change in population of the different single particle states in projectile and target is quite small. At last I want here to remind that the outcome of the reaction is determined by the well known form factors for one-particle transfer and the excitation of collective states, from the actual binding energies of the two nuclei and by the average single particle level density. The actual values of the cross sections for the different channels are determined by the width of the Q-value windows that is centered at the optimum Q-value.

3. Comparison with the data

In the last few years at the Laboratori Nazionali di Legnaro (INFN Italy) a systematic study of transfer reactions has been undertaken in the hope to elucidate the importance of transfer degrees of freedom in the enhancement of fusion below the Coulomb barrier and in understanding the transition from the quasi-elastic to the deep-inelastic regimes. With this perspective in mind a new 'time of flight spectrometer' (PISOLO) [15] has been built with a mass and charge resolution such that all the individual fragments produced in the reaction could be identified. The acceptance of the spectrometer is quite large so that very weak channels and accurate angular distributions and excitation functions can be measured.

Let me start with the last measurement concerning the ^{64}Ni + ^{238}U collision at a bombarding energy of 390 MeV where transitions up to 6 protons and 6 neutrons have been clearly identified [9]. To have an overview of the results, figure 1 shows the total cross sections, obtained after integration of the angular and Q-value distributions for all the channels where statistics is reasonable together with calculations.

First of all let me remark how well theory reproduces the data for pure neutron transfer channels demonstrating the correct treatment of neutron transfer (0p) on the basis of independent single neutron transfer modes (cfr. also ref. [10,11]). Also well predicted are

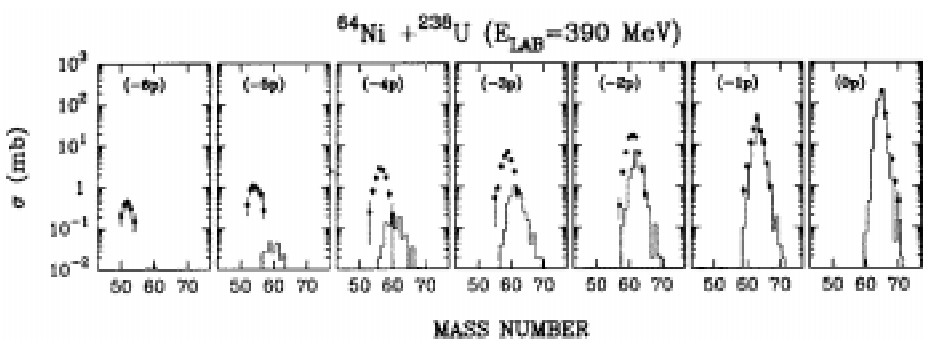

Figure 1. Experimental (points) and calculated (histograms) angle- and Q-value integrated cross sections for the indicated transfer products.

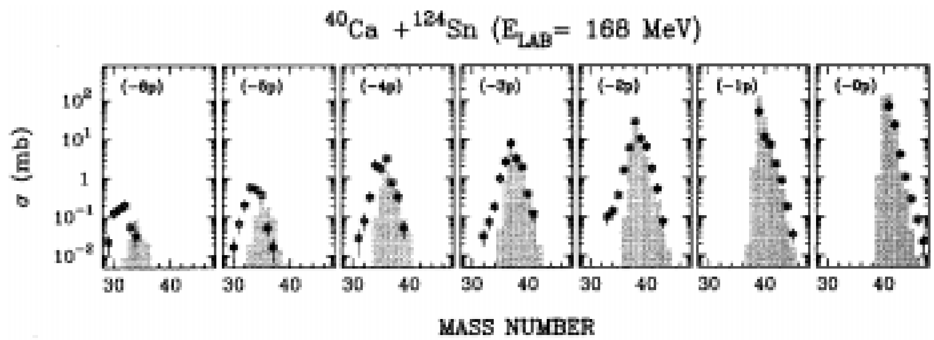

Figure 2. Experimental (points) and calculated (histograms) angle- and Q-value integrated cross sections for the indicated transfer products.

the isotope distributions for the $(-1p)$ case, but, as one moves along the proton stripping direction, one sees that the theory under predicts the population of the light isotopes despite maintaining a good agreement in the neutron pick-up side (heavy isotopes). These discrepancies become more and more evident moving toward channels with more transferred protons. Always from figure 1 one notices that for the $-2p$, $-4p$ and $-6p$ channels the maxima of the isotope distribution peak at channels corresponding to the transfer of $-2n$, $-4n$ and $-6n$ pointing to a possible evidence of multiple α-transfer channels. This is however not the case since no odd-even staggering is present in the data, the isotope distributions evolve, as a function of the number of transferred protons, in a very smooth and regular way suggesting that also the protons behave as independent objects in the transfer process.

Very similar results were observed in other reaction [12–14], here I show just the isotope distribution for the ^{40}Ca + ^{124}Sn collision at a bombarding energy of 186 MeV [12]. From figure 2, one can draw the same consideration as discussed for the ^{238}U case.

The theory, outlined above, not only allows the calculation of inclusive isotope distributions but also the calculation of angular distributions and excitation energy spectra. In figure 3, in comparison with the data, are shown the angular distribution of several channels. The continuous line corresponds to the calculation performed with the program GRAZING [4]. The agreement is quite good in all the angular range. When many nucleons are transferred the theory under predicts the cross section at forward angle where contributions from more complicated reactions (deep-inelastic) may be important. The theory is not in a condition to calculate the angular distribution of channels with neutron stripping. As it is well known for stable nuclei the only open channels are proton stripping and neutron pick-up since the other, neutron stripping and proton pick-up, are strongly hindered by optimum Q-value considerations. One is thus led to conclude that these channels are populated in the experiment by more complicated processes (see below).

At last, let me show in figure 4 for some selected channels the total kinetic energy loss (TKEL) spectra. As it is apparent, the theory gives a good description for the average energy-loss but has the tendency to underestimate the long tail of the distributions. It is important also to notice that the transfer processes populate channels at high excitation energy. This, via evaporation, may influence the final yields of the fragment distributions.

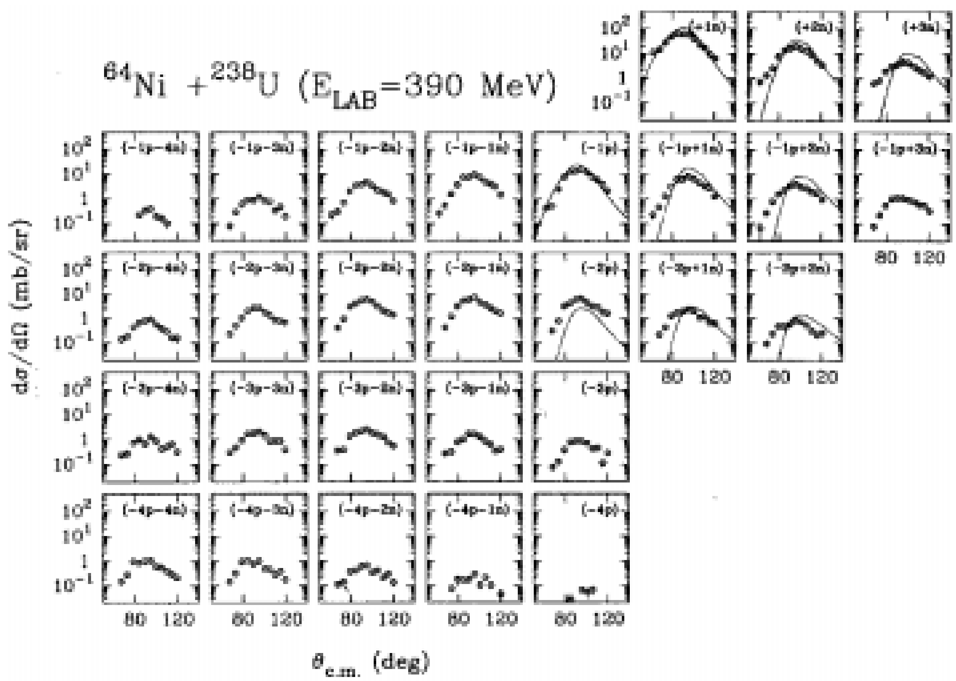

Figure 3. Experimental (points) and theoretical (lines) Q-value integrated angular distributions for the indicated transfer channels.

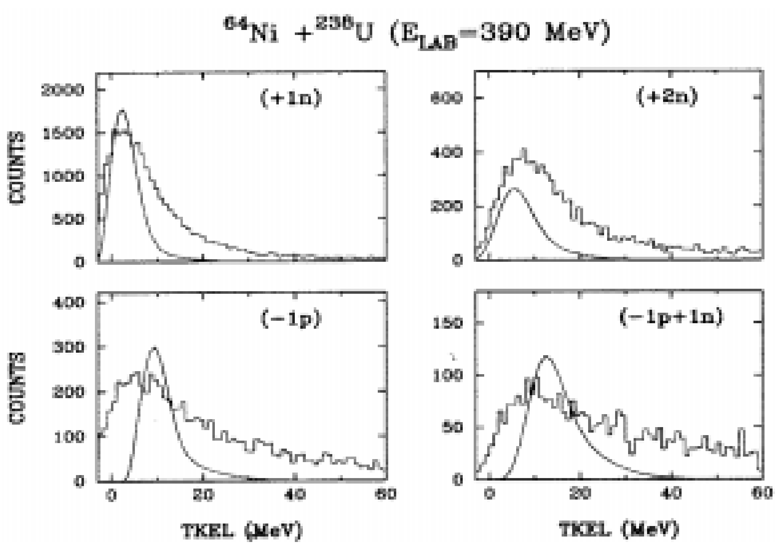

Figure 4. Experimental (histograms) and theoretical (lines) total kinetic energy loss (TKEL) distributions for the indicated transfer channels.

4. Neutron evaporation

To get a deeper insight into the behavior of the experimental yields in figure 5 we plot, again, the total cross sections for the ^{64}Ni + ^{238}U, this time not as a function of the mass number (as in figure 1) but as a function of the number of transferred protons (ΔZ). In the left-hand side we display the cross sections involving neutron pick-up while in the right-hand side the ones involving neutron stripping (notice that the neutron stripping side reaches the $-6p$ while the neutron pick-up side stop at $-4p$). As it is apparent from this kind of plot the neutron pick-up and neutron stripping reactions have a very different behavior. The neutron pick-up decrease in a very smooth way as the number of transferred protons increase, while neutron stripping reactions have a maxima when the number of transferred protons is almost equal to the number of transferred neutrons. This is a clear indication that the two kinds of reactions are populated by different mechanism. While the neutron pick-up side indicates a direct population in terms of independent transfer of neutrons (pick-up) and protons (stripping) the neutron stripping side shows that the yield of these reactions have to depend on more complicated mechanism.

From optimum Q-value arguments one knows that neutron stripping reactions are strongly hindered in collisions among stable nuclei so the channels involving neutron stripping cannot be populated via this mechanism. The first alternative mechanism that came in mind is the neutron evaporation (we know from figure 4 that transfer reactions populate

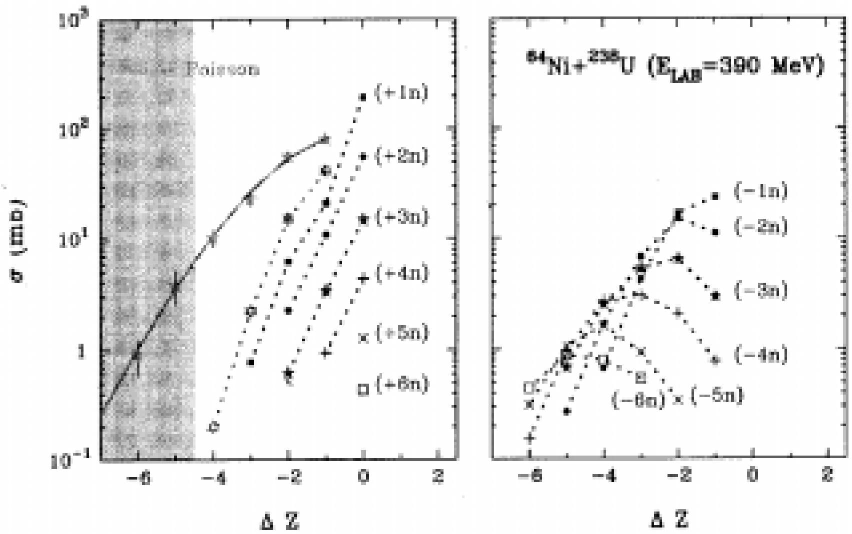

Figure 5. Experimental total cross sections as a function of the number of transferred protons ΔZ for channels involving neutron pick-up (left side) and neutron stripping (right side). To guide the eye we connected, with a dash line, the different proton transfer channels corresponding to the equal number of neutron. The symbol with no label corresponds to the $(0n)$ channels. The full line is a Poisson distribution, normalized to the data. The point close to this line are obtained by adding to each pure proton transfer $(0n)$ channels all those corresponding to neutron stripping.

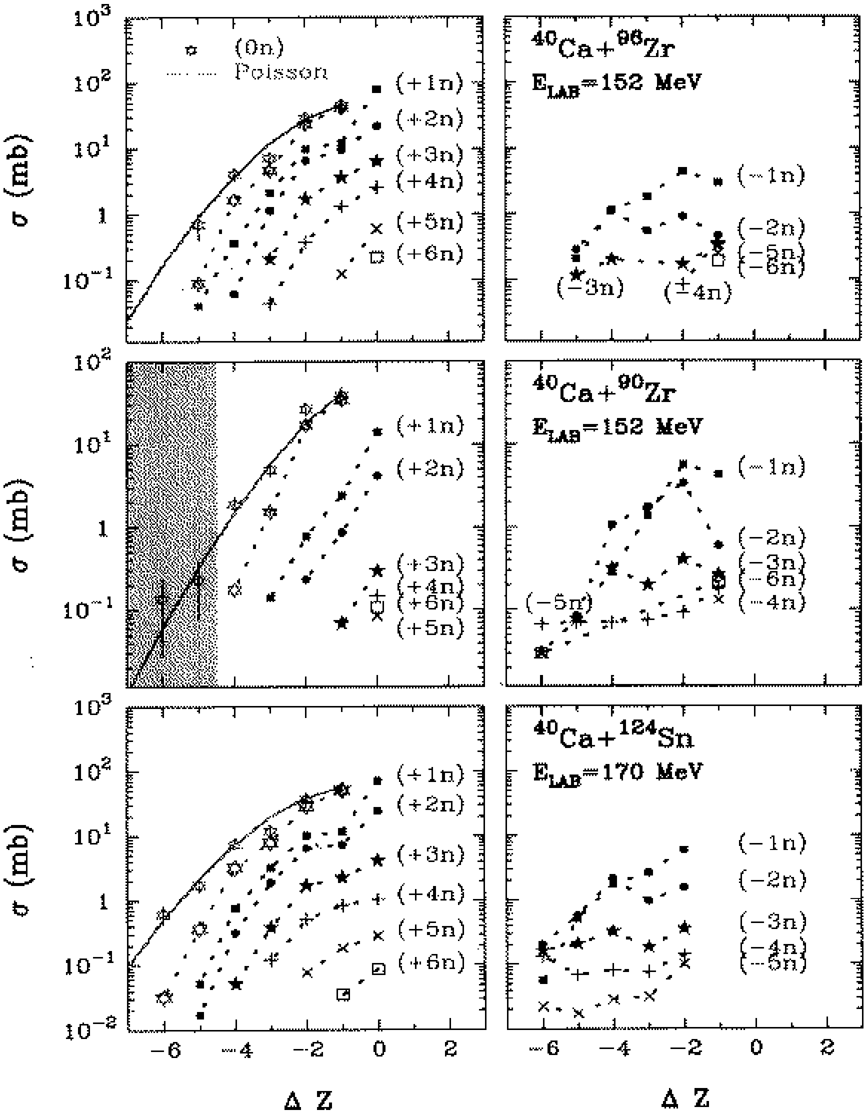

Figure 6. Experimental total cross sections as a function of the number of transferred protons ΔZ for channels involving neutron pick-up (left side) and neutron stripping (right side) for the indicated reactions. Cfr. figure 5 for more details.

predominantly at highest excitation energy and we remind that in the experiment only the light fragment is identified). It is thus tempting to add, for each ΔZ, the cross section of all the neutron stripping channels. In doing so one obtains the points labelled with stars on the left-hand side of figure 5.

These can be nicely fitted (full line) with a Poisson distribution defined by an average number of 2. Since the Poisson distribution describes the transfer of independent modes, it is clear that this finding points into the direction that also protons are transferred independently.

It is clear that if evaporation influences the isotope distribution this must be a common feature of the multinucleon transfer reactions. We thus apply the same reasoning to all the reactions for which multinucleon transfer reactions have been measured. In figure 6 we display for the indicated reaction the isotope distribution. In all cases the cross section obtained by adding to the pure $-0p$ channels all the one involving neutron stripping are all nicely fitted by Poisson distribution with an average number ranging 1.8 for the ^{40}Ca + ^{90}Zr to 2.2 for the ^{40}Ca + ^{124}Sn reactions. It is quite likely that this systematic behavior of the inclusive cross section indicate that also protons behave like independent particle in a transfer process.

5. Conclusion

In this talk I discussed transfer reaction among heavy ions. I hope I convince you that the main features of these reactions can be understood in term of independent single particle transfer. I also discussed the importance of neutron evaporation in determining the final isotope distribution.

References

[1] A Winther, *Fisika* **22**, 41 (1990)
[2] A Winther, *Nucl. Phys.* **A572**, 191 (1994)
[3] A Winther, *Nucl. Phys.* **A594**, 203 (1995)
[4] A Winther, *Program GRAZING*, unpublished
[5] R A Broglia, G Pollarolo and A Winther, *Nucl. Phys.* **A361**, 307 (1981)
[6] G Pollarolo, R A Broglia and A Winther, *Nucl. Phys.* **A406**, 369 (1983)
[7] C H Dasso, S Landowne, G Pollarolo and A Winther, *Nucl. Phys.* **A459**, 134 (1986)
[8] R A Broglia and A Winther, *Heavy Ion Reactions*, Part I and II, Frontiers in Physics, vol. 84 (Addison-Wesley, 1991)
[9] L Corradi, A M Stefanini, C J Lin, S Beghini, G Montagnoli, F Scarlassara, G Pollarolo and A Winther *Phys. Rev.* **C59**, 261 (1998)
[10] C L Jiang, K E Rehm, J Gehring, B Glagola, W Kutschera, M Rhein and A H Wuosmaa, *Phys. Lett.* **B337**, 59 (1994)
[11] C L Jiang, K E Rehm, H Esbensen, D J Blumenthal, B Crowell, J Gehring, B Glagola, J P Schiffer and A H Wuosmaa, *Phys. Rev.* **C57**, 2393 (1998)
[12] L Corradi, J H He, D Ackermann, A M Stefanini, A Pisent, S Beghini, G Montagnoli, F Scarlassara, G F Segato, G Pollarolo, C H Dasso and A Winther, *Phys. Rev.* **C54**, 201 (1996)
[13] L Corradi, A M Stefanini, J H He, S Beghini, G Montagnoli, F Scarlassara, G F Segato, G Pollarolo and C H Dasso, *Phys. Rev.* **C56**, 938 (1997)
[14] G Montagnoli and A Stefanini, private communication
[15] G Montagnoli, F Scarlassara, S Beghini, G F Segato, D Ackermann, L Corradi, He Jian-Hua, A Pisent and A M Stefanini, Legnaro Annual Report 1994, Report LNL-INFN (Rep)-095/95, 1995, p. 205