The evolution from quasi-elastic to deep inelastic processes and its connection to fusion

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Abstract. Substantial experimental and theoretical efforts have been made in the last decade to study into detail the transition from quasi-elastic to deep inelastic processes in heavy ion collisions. The understanding of this transition is relevant not only to probe which degrees of freedom play a role in the multinucleon transfer process but also for its connection with near barrier fusion reactions. A boost in the field has been given with the implementation of large solid angle magnetic spectrometers coupled to γ arrays with which extensive investigations have been carried out for nuclear structure and reaction dynamics. In the present paper aspects of these studies will be presented, with emphasis on processes undergoing significant energy loss in binary collisions.

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 [2, 3], the transition from the quasi-elastic to the deep-inelastic regime [4] 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 [5] and Fusion08 [6] conferences. A yet 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.

From the theoretical point of view different regimes have been historically treated on completely different bases (see Fig.1). In the quasi-elastic regime (few transferred nucleons and small energy losses) one or, at most, two-nucleon transfer has been treated using Distorted Wave Born Approximation or Coupled Channel codes, while in the deep inelastic regime (many transferred nucleons and large energy losses) stochastic, friction or diffusion models have been used [7]. From the experimental point of view, nuclei produced in transfer reactions have been identified with good A, Z and Q-value resolutions for medium-light systems, but channel detection was limited to the transfer of 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, nuclear charge identification was possible without mass or energy resolution.

The ”transition” regime, where many nucleons are transferred and where nuclear structure effects still play a significant role in the dynamics, represents a window not well studied in its detail and for which both experimental and theoretical advances have been recently made. Thanks to the development of high resolution and high efficiency experimental set-up’s one
could 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. [8, 9, 10] and references therein). The advent of the last generation large solid angle magnetic spectrometer PRISMA [11, 12] 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 [13] 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 [14, 15, 16, 17]. 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 (see e.g. Ref. [18] and references therein).

2. Quasi elastic and deep inelastic processes: some concepts

Before discussing some important features present in quasi-elastic processes I here remind some basics of deep inelastic collisions, which lead to interpretations based on diffusion or stochastic models [7, 19]. In Fig. 2 it is shown, for the reaction $^{86}$Kr+$^{166}$Er [20], how the Total Kinetic Energy (TKE) of the reaction products depends on nuclear charge Z (top left) and angle (bottom left). One clearly sees how the (mass integrated) Z distributions widen with energy loss, promptly suggesting some kind of nucleon diffusion process. Events show up at energies lower than the Coulomb barrier for two touching spheres configuration ($V_c$) indicating that nuclei may undergo strong deformation before reseparation. The Wilczynski plot shown on the bottom left of the figure displays a characteristic behaviour of the binary process, where quasi-elastic and deep inelastic events are associated with high TKE and broader distributions, respectively. This
behaviour has a definite dependence on the size of the Coulomb field, ranging from an orbiting to a focussing condition up to a change of structure of the lower ridge for very heavy systems. This suggested that in a reaction plane defined by the beam axis and detection angle two components may show up as depicted in part a) of Fig. 2. The two branches are associated with impact parameters on the right or left hand side of the beam axis, represented by full lines and dashed lines, respectively, in part b) of Fig. 2. A dinuclear configuration can be formed, explained macroscopically as the effect of the rotation of the binary system in turn correlated with large energy losses (long interaction times). This simple picture was at the basis of various phenomenological interpretations of experimental data [19].

Figure 2. Left: matrixes of Total Kinetic Energy (TKE) vs. nuclear charge Z (top) and vs c.m. angle $\theta_{cm}$ (bottom) for the reaction $^{86}\text{Kr}+^{166}\text{Er}$ at the indicated energy. Right: Wilczynski plot indicating the distributions of events in deep inelastic collisions (panel a)) and its interpretation (panel b), adapted from Refs. [19, 20]).

To introduce the discussion on quasi elastic processes I show in Fig. 3 a representative example of the mass and charge distribution of transfer products in the $^{40}\text{Ca}+^{208}\text{Pb}$ system [9]. The bombarding energy is close to the Coulomb barrier and the yield, measured at the grazing angle, reflects some of the main characteristics of quasi-elastic processes. These may be appreciated by plotting on the same figure three lines, the two dash-dotted lines correspond to pure neutron pick-up and pure proton stripping channels, while the full line represents the charge equilibration, namely the location of the N/Z ratio of the compound nucleus. One sees that most nuclei are located on the left side of the charge equilibration line, indicating the dominance of a direct mechanism in the population of different fragments. Notice also that for the massive proton transfer channels the isotopic distributions drift towards lower masses, a clear indication that these distributions are affected by evaporation processes (see later).

An interpretation of these distributions can be done on the basis of semiclassical arguments,
where nuclear structure and kinematic properties are taken into account via the introduction of form factors $f_{\beta \alpha}$ [21, 22] and optimum Q-value window, respectively (see Ref. [22] for details). To estimate the magnitude of a given transfer process it is not necessary to solve explicitly the full system of coupled equations but it suffices to write down its first order Born approximation (here I follow the discussion more widely presented in Ref. [1]). For a given impact parameter (incoming partial wave $\ell$) the probability for the transition from the entrance channel $\alpha$ to the channel $\beta$ may be written in the form

$$P_{\beta \alpha}(\ell) = \frac{\hbar}{i} \int_{-\infty}^{+\infty} dt \ e^{i\sigma_{\beta \alpha} f_{\beta \alpha}(0, r) e^{i(E_\beta - E_\alpha + (\delta_\beta - \delta_\alpha)) t / \hbar}}$$

where the time integral has to be performed along the classical trajectory for the given partial wave $\ell$. In direct processes the two nuclei barely overlap, so that only the tail of the formfactor is relevant. By approximating the true trajectory with a parabolic parameterisation around the turning point the above transition probability may be written in the form

$$P_{\beta \alpha} = \sqrt{\frac{1}{16\pi\hbar^2 |\vec{r}_0|^2 |f_{\beta \alpha}(0, r_0)|^2}} g(Q_{\beta \alpha})$$

where $\vec{r}_0$ is the radial acceleration at the distance of closest approach $r_0$ for the grazing partial wave. The adiabatic cut-off function $g(Q)$ is defined as

$$g(Q) = \exp\left(-\frac{(Q - Q_{opt})^2}{\hbar^2 |\vec{r}_0|^2 |\kappa_{\alpha\alpha'}|^2}ight)$$

where the optimum Q-value is

$$Q_{opt} = \left(\frac{Z_d}{Z_A} - \frac{Z_d}{Z_b}\right) E_B + \left(\frac{m_d}{m_b} - \frac{m_d}{m_A}\right) (E - E_B)
+ \frac{m_d\vec{r}_0}{m_a + m_A} (R_A m_b - R_0 M_B),$$

Figure 3. $\Delta E - E$ plot (left) and mass-charge distributions (right) of transfer products in the $^{40}\text{Ca} + ^{208}\text{Pb}$ reaction at $E_{lab} = 235$ MeV obtained at the grazing angle, $\theta_{lab} = 84^\circ$. The dash-dotted lines correspond to the pure proton stripping ($\Delta Z$) and to the pure neutron pick-up ($\Delta N$) channels, crossing at $Z = 20$ and $A = 40$. The full line shows the charge equilibration, namely, the N/Z ratio of the compound nucleus (from Ref. [9]).
$E_B$ is the Coulomb barrier and $m_d$ and $Z_d$ are the mass and charge of the transferred particle. The adiabatic cut-off function $g(Q)$ defines the actual value of the transition probability, the maximum being at the optimum Q-value. This derives from the requirement that the trajectory of entrance and exit channels matches smoothly close to the turning point where the contribution of the formfactor peaks. Notice that the bombarding energy dependence of the cut-off function is contained in the $\tilde{r}_0$ term that defines its width (inversely proportional to the collision time).

![Figure 4](image)

**Figure 4.** Adiabatic cut-off functions for one and two neutron and proton transfer channels for the reaction $^{58}\text{Ni}^{+208}\text{Pb}$ at the indicated energy (Q-value in MeV). The horizontal lines represent the location of all possible transitions.

A rough estimation of the total cross section for a particular transfer channel can be obtained by simply performing a Q-value integration of equation (2). In Fig. 4 the adiabatic cut-off function $g(Q)$ for all one and two particle transfer channels is shown for the $^{58}\text{Ni}^{+208}\text{Pb}$ reaction. In the same figure with horizontal lines are represented, for all channels, the location of all possible transitions. Since only the channels whose Q values lie below the bell shaped curve can actually occur, it is clear that the only allowed transfers are neutron pick-up and proton stripping. All the other channels are hindered by optimum Q-value consideration. From the same figure one notices that for some channels, in particular the two proton stripping and two neutron pick-up, the reaction mechanism favours transitions leading to high excitation energies.

These simple findings have been demonstrated in almost all measured systems. An example is shown in Fig. 5 where the isotopic distribution of the different charges populated in the indicated reactions [8, 23] are plotted. One observes that the strongest channels are those corresponding to the neutron pick-up and proton stripping processes as the optimum Q-value rule suggests. It is only for charges far from the entrance channel that one observes sizeable contributions that seems to derive from the stripping of neutrons, this is particularly evident for
Figure 5. Isotopic distributions for the transfer channels up to the stripping of four protons are shown for the reaction $^{64}$Ni + $^{238}$U at 390 MeV bombarding energy (top) and for the reaction $^{58}$Ni + $^{208}$Pb at 328 MeV bombarding energy (bottom). The shadowed regions mark the transition from neutron stripping to neutron pick-up. Data are from Refs. [8, 23].

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characteristic indicates that the process is very fast the large energy losses indicates that the two ions, before the emerging point, acquire large deformations. These two conflicting findings, short collision time and large energy losses, suggested that in the evolution of the reaction the excitation of surface modes is playing an important role being the low lying modes the main source for the formation of the large deformations.

Figure 6. Total cross sections for multinucleon transfer channels populated in the $^{58}$Ni+$^{208}$Pb reaction. Points are the experimental data, histograms are calculations performed with semiclassical theory taking into account independent particle transfers (top), an additional pair mode (middle) and including nucleon evaporation effects from the primary fragments (bottom) (from Ref. [8]).

It was the necessity to have a description of the reaction able to treat at the same time quasi-elastic and deep inelastic events that lead to the development of the reaction code GRAZING [28, 29, 30]. Fig. 6 shows as representative example the comparison between experimental and theoretical total transfer cross sections for the multinucleon transfer channels populated in the $^{58}$Ni+$^{208}$Pb reaction [8]. In the top row the data are compared with calculations performed with the semiclassical theory. In GRAZING, the treatment of the transfer degrees of freedom is based on the 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. Surface degrees of freedom and particle transfer are treated on the same footing, and 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 [1] and can reproduce the near-barrier fusion excitation functions [31] and extracted barrier distributions [32]. The theory describes pretty well the pure neutron transfer and the (-1p) isotopes but underestimates considerably all the other charges. However, we stress that GRAZING accounts correctly for almost 80% of the direct transfer yield. For the explanation of the discrepancies at large charge transfers, it is very difficult at this stage to say what is missing in the model, as degrees of freedom or as reaction mechanism.

To understand the charge distribution it was added in the calculation the contribution of a direct pair mode both for neutrons and protons, by using the macroscopic formulation. Since the code GRAZING does not allow to add these pair degrees of freedom, one used another code, based on the CWKB approximation. Its main characteristics is that for the single particle transfer it uses the actual distribution of single particle levels that are coupled with the true formfactors (it has been developed to check the different approximations that are included in the GRAZING program). The multinucleon transfer in obtained via a successive mechanism that mimic the approximation of GRAZING. For the relative motion the program uses the WKB approximation and it is constructed to reproduce the ordinary DWBA calculations for the one-particle transfer channels (for more details confer Ref. [9]). To keep at minimum the number of parameters one choose to add a single pair mode placed at the optimum Q-value and one used the strength of the form factor (kept the same for neutrons and protons) to fit the pure -2p channel. The results of such a calculation are shown in the middle row of the figure. Notice that the pair mode alters very little the cross section for neutron transfer but is essential for the proton transfer. Here one stresses that the pure one neutron pick-up is much larger (almost a factor 10) with respect to the pure one proton stripping transfer. This may mask the effect of the pair mode since the successive mechanism gives a much larger contribution for neutrons than for protons.

These semiclassical models provide the excitation energy of the single fragments thus one is in condition to correct the primary yield for the evaporation process. The final yields distributions are shown in the bottom row of the figure where now a reasonable overall description is obtained.

Similar kind of results have been achieved in more recent data obtained with large solid angle spectrometers, in particular in the $^{90}\text{Zr}+^{208}\text{Pb}$ and $^{40}\text{Ca}+^{96}\text{Zr}$ systems. The effects attributed to neutron evaporation, indirectly visible from the analysis of Refs. [8, 9, 23], have been directly observed by means of particle-$\gamma$ coincidences [10] (see next Section).

4. Energy loss effects
The Z and A identification capability and the large detection efficiency of the magnetic spectrometer PRISMA allows to follow the evolution of the reaction from the quasi elastic to the deep inelastic regime. Here, one 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.

The power of these new spectrometers can be appreciated from Fig. 7 which shows the total angle and Q-value integrated yields for multineutron and multiproton transfer channels populated in the reaction $^{90}\text{Zr}+^{208}\text{Pb}$. Isotope identification in the proton transfer direction is visible down to ($-8p$) stripping, but sensitivity was sufficient to observe even more proton stripping channels.

The TKEL spectra of the different transfer channels for the same reaction are shown in Fig. 8. One can here follow the evolution pattern as function of the number of transferred neutrons and protons. In the case of pure neutron transfer one sees a quasi-elastic peak and an increasing strength of large energy loss components when adding neutrons. When protons are involved one observes a faster growth of large TKEL components, up to the point that beyond three
proton stripping the TKEL distributions have almost similar shapes. For channels which, due to optimum Q-values, are not directly populated, the corresponding TKEL shapes 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. One should remind that one detects secondary fragments and that the TKEL spectra are constructed assuming binary reactions, so the shapes may be somewhat distorted with respect to the (unreconstructed) primary fragments.

In the top row are shown the mass distribution associated to the different nuclear charges. One sees that the mass yields of pure proton stripping channels (circles) become less favourite as more protons are transferred, with a mass distributions shifting to lower values.

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 [8, 9, 23]. 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. 9 for the for the -2p + 2n channel populated in the 40Ca+96Zr reaction [10]. About 60%
Figure 8. TKEL spectra obtained in the reaction $^{90}\text{Zr}+^{208}\text{Pb}$ 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 vertical scales are different for the various proton stripping channels.

of the yield corresponds to the primary $^{96}\text{Mo}$, 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 ($Q_{\text{opt}} \simeq 0$), while in the proton stripping channels larger TKEL are observed, thus the neutron evaporation has a stronger effect on the final mass partition.

That the exchange of nucleons may constitute the main source for the dissipation of energy can be understood with a very simple model. Let’s suppose to have a system for which $N$ independent single-particle transitions can occur all with the same probability $p$. In such a system the probability to have the transfer of $n$ particles is simply given by the binomial
Figure 9. $\gamma$ spectra for the $-2p + 2n$ channel in the reaction $^{40}\text{Ca} + ^{96}\text{Zr}$ Doppler corrected for the heavy (top two frames) and light fragments (bottom frame). To have a better identification of the different $\gamma$ lines for the heavy fragment an expanded energy scale has been used (from Ref. [10]).

distribution:

$$P_n = \binom{N}{n} p^n (1 - p)^{N-n}$$  \hspace{1cm} (5)

For this distribution the average number of transferred particles is $\langle n \rangle = pN$ so that the corresponding average energy loss is $\langle E_{\text{loss}} \rangle = \langle n \rangle Q$. In a heavy-ion collision the number of open channels is very large ($N \sim 100$) so that with $p \sim 0.1$ one estimates an average number of transferred nucleons of the order of 10 and an average energy loss of 50 MeV if for each transition one loses 5 MeV. As this simple example shows, particle transfer may provide the main source for the dissipation of energy.

5. Transfer and fusion processes

I have outlined in the previous sections the importance of large energy loss components in multinucleon transfer processes. The understanding of these processes and its microscopic interpretation is important not only for the transfer in itself but also for its connection with near barrier fusion. To set the frame, for medium mass systems one can roughly distinguish three energy regions, as pictorially depicted in Fig. 10.

At energies well above the Coulomb barrier the transmitted flux $T$ (capture) is larger than the reflected flux $R$ (transfer), i.e. fusion dominates over transfer. However fusion does not necessarily happen when the barrier is overcome, for instance the reaction may develop large TKEL (deep inelastic, which overlap to some extent with quasi-fission processes).
Figure 10. How transfer and fusion compare in different energy ranges. Above the Coulomb barrier (\(E_b\)) fusion can be less than capture, at the barrier fusion and transfer are roughly comparable and this is the region where coupled channel effects play a role, at sub barrier energies transfer dominates over fusion.

At energies close to the barrier transfer and fusion have comparable cross sections. This is the energy region where coupled channel effects set-in. Due to couplings of the elastic channel to inelastic and possibly transfer channels, the kinetic energy of the two colliding ions is no more well defined and the scattering process can be seen as if the barrier fluctuates. This effect is well known and has given rise to a wealth of experimental and theoretical work (cfr Refs. [5, 6] and references therein).

At energies below the barrier fusion cross sections drop exponentially and transfer dominates. This is the ideal region to study nucleon-nucleon correlation effects since on one side transfer data are not affected by evaporation (small TKEL) and on the other side theoretical predictions have less ambiguities (choice of the nuclear potential).

5.1. Energies near and above the Coulomb barrier
A debate at energies near and above the Coulomb barrier emerged in connection with the fact that experimental fusion cross sections in different cases turn out to be less than capture. Such an hindrance phenomenon has been suggested to possibly originate to an inadequacy of the nuclear potential which otherwise well fits elastic scattering data [33]. Among alternative explanations is the possibility that other competing channels, like deep inelastic or quasi fission, strongly contribute to capture and have to be taken into account.

To discuss this point one can take as representative example the \(^{58}\text{Ni}+^{124}\text{Sn}\) system where a complete set of data exist for both evaporation residue, fission, transfer and deep inelastic [34]. These data are shown in Fig. 11, in comparison with the calculations [35] performed with the code GRAZING, which has been already shown to well reproduce the transfer cross sections and the elastic scattering for many systems. The model is also able to estimate the capture cross section, and this is shown in the same figure.
From this comparison one sees that the experimental sum of evaporation residue and fission cross sections is indeed less than the calculated capture. However, for this system deep inelastic components have been measured at different bombarding energies and shown to represent a significant fraction of the total reaction cross section [36]. By adding these cross sections to the evaporation residue and fission ones one gets a reasonable agreement with capture.

This analysis shows once more the importance of the deep inelastic components and stresses the importance to get complete set of data for other systems, since the systematics is at present too scarce. Its relevance is connected also to the concept of barrier distributions. As said before, the effect of the couplings to the intrinsic degrees of freedom of the system can be depicted as giving rise to a smearing over several energies of the Coulomb barrier [37]. These barrier distributions can be extracted from the fusion excitation function by taking the second derivative of the energy weighed fusion cross sections [38]. It has been suggested that a similar information can be derived from the energy dependence of the quasi-elastic cross sections at backward angles [39]. The barrier distribution obtained with these two methods turn out to be in reasonable agreement with each other, although the ones extracted from quasi-elastic are somewhat broader and with less structure. A recent analysis [32] showed how the barrier distribution obtained from quasi-elastic cross sections depends on what one considers as quasi-elastic, so one may expect a difference with respect to the results obtained from the fusion cross sections. While what one extracts from fusion reactions [31] reflects how the couplings modify the transmission coefficient, what one gets from quasi-elastic reflects the modification of the reflection coefficient. If fusion and quasi-elastic scattering exhaust most of the total reaction cross section the barrier distributions are expected to be quite similar. However, for heavy systems, where the reaction is dominated by complicated processes like deep inelastic where the nuclei may overcome the Coulomb barrier but separate again with large energy losses and mass transfer, caution must be taken in the interpretation. In the analysis of different heavy
ion systems where excitation functions have been measured from above to below the Coulomb barrier [40], a careful analysis had to be done in order to disentangle quasi-elastic from deep inelastic components, so as to get the experimental barrier distributions.

5.2. 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. 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:

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

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 $e^{i\omega_{ij}}$ 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 [41, 42]. This fact should provide a simpler analysis of the data.

\[\text{Figure 12.} \quad \text{Mass distributions for pure neutron transfer channels obtained in the reaction} \ \^{94}\text{Zr}^{+^{40}}\text{Ca at the indicated bombarding energies. Ca-like recoils have been detected at } \theta_{\text{lab}}=20^\circ \text{ with the PRISMA spectrometer.}\]

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 $\theta_{\text{cm}} \approx 180^\circ$. 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 previously measured with high precision [43] and a complete set of data for both multinucleon transfer and fusion reactions would provide an excellent basis for coupled channel calculations.

In Fig. 12 are shown 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 $Q$-value distributions for the $+2n$ channel at the lowest energies are very narrow and at a few MeV above the ground to ground state transitions 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.

6. Summary and outlook
In this paper I discussed how the two regimes of quasi elastic and deep inelastic processes, treated historically on very different footing both experimentally and theoretically, can be connected. This transition regime has been extensively studied in the last decade.

New opportunities are offered by the implementation of large acceptance spectrometers based on trajectory reconstruction. With these devices one gained more than an order of magnitude in the total efficiency while keeping good resolution for the detection of heavy ion transfer products. In coupling them with $\gamma$ arrays, one can now study the transfer yield to specific final states and their decay modes. The experimental yields have been analyzed with semiclassical theories developed to calculate at the same time quasi-elastic and deep-inelastic processes. These theories have been able to provide a consistent description of transfer and fusion reactions by using few degrees of freedom, surface modes and single particles.

It has been shown how energy loss develops in multinucleon transfer processes, in dependence on the specific mass and charge of transfer reaction products and how it can be associated to nucleon evaporation effects. The correct treatment of these processes is very important to predict yields of nuclei far from stability exploiting binary reactions. It is also important to keep in mind that, although primary yields of heavy transfer products may be large, in addition to evaporative processes the heavy fragments may be affected by fission. This fact is of relevance for the production of neutron rich nuclei, a field of growing interest, particularly in those areas connected with $r$-processes (for instance the region below $^{208}$Pb) or with heavy elements. Therefore, experiments aiming at measuring directly the cross sections and spectroscopy of heavy partners and the survival probability of the heavy partner against fission should be pursued in the future. Interesting are the neutron rich regions of the actinides and transactinides which cannot be reached by fission or fragmentation reactions.

More in general, much wider investigations in the field are required, for instance at sub-barrier energies where nuclei enter into contact through the long tail of the nuclear densities. It is in these regions that, for very neutron-rich nuclei, information on nucleon-nucleon correlation could be obtained by studying the excitation functions of specific transfer channels.
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References
[1] Corradi L, Pollarolo G and Szilner S 2009 J. of Phys. G 36 113101
[2] Wu C Y, von Oertzen W, Cline D and Guidry M 1990 Annu. Rev. Nucl. Part. Sci. 40 285
[3] Von Oertzen W and Vitturi A 2001 Rep. Prog. Phys. 64 1247
[4] Rehm K 1991 Annu. Rev. Nucl. Part. Sci. 41 429
[5] Fusion06: Int. Conf. on Reaction Mechanisms and Nuclear Structure at the Coulomb barrier, S. Servolo (Venezia), Italy, March 19-23, 2006, AIP Proceedings Series, Vol. 853, Melville (New York), Corradi L et al eds
[6] Fusion08 : Int. Conf. on New Aspects of Heavy Ion Collisions Near the Coulomb Barrier, Chicago (USA), September 22-26, 2008, AIP Proceedings Series, Vol. 1098, Melville (New York), Rehm K E et al. eds.
[7] Schröder W U and Huizenga 1984 Treatise on Heavy-Ion Science Vol.2 Plenum, Bromley D A ed
[8] Corradi L et al 2002 Phys. Rev. C 66 024606
[9] Szilner S et al 2005 Phys. Rev. C 71 044610
[10] Szilner S et al 2007 Phys. Rev. C 76 024604
[11] Stefanini A M et al 2002 Nucl. Phys. A 701c 217
[12] Corradi L 2010 Nucl. Phys. A 853 129
[13] Gadea A et al 2002 Eur. Phys. J. A 20 193
[14] Marginean N et al 2006 Phys. Lett. B 633 296
[15] Lunardi S et al 2007 Phys. Rev. C 76 034303
[16] Valiente-Dobon J J et al 2008 Phys. Rev. Lett. 102 242502
[17] Brosa R et al 2010 Phys. Rev. C 82 034319
[18] Corradi L et al 2002 Nucl. Phys. A 701 109c
[19] Gobbi A and Nörenberg Heavy Ion Collisions Vol.2 Bock R ed, North Holland 1980
[20] Rudolf G et al 1979 Nucl. Phys. A 330 243
[21] Quesada J M, Pollarolo G, Broglia R A and Winther A 1985 Nucl. Phys. A 442 381
[22] Broglia R A and Winther A Heavy Ion Reactions (Addison-Wesley Pub. Co., Redwood City CA, 1991)
[23] Corradi L et al 1999 Phys. Rev. C 59 261
[24] Dasso C H, Pollarolo G and Winther A 1994 Phys. Rev. Lett. 73 1907
[25] Buttle P J A and Goldfarb L J B 1966 Nucl. Phys. 78 409
[26] Brink D M 1972 Phys. Lett. B 40 37
[27] Sørensen J H, Pollarolo G and Winther A 1989 Phys. Lett. B 225 41
[28] Winther A program GRAZING, http://www.to.infn.it/~nanni/grazing
[29] Winther A 1994 Nucl. Phys. A 572 191
[30] Winther A 1995 Nucl. Phys. A 594 203
[31] Pollarolo G and Winther A 2000 Phys. Rev. C 62 054611
[32] Pollarolo G 2008 Phys. Rev. Lett. 100 252701
[33] Newton J O et al 2004 Phys. Rev. C 70 024605
[34] Esbensen H, Jiang C L and Rehm K E 1998 Phys. Rev. C 57 2401
[35] Pollarolo G 2007 Nucl. Phys. A 878 207c
[36] Wolfs F L H 1987 Phys. Rev. C 36 1379
[37] Esbensen H 1981 Nucl. Phys. A 352 147
[38] Roweley N, Satchler G R and Stelson P H 1991 Phys. Lett. B 254 25
[39] Timmers H et al 1995 Nucl. Phys. A 584 190
[40] Mitsuoka S et al 2007 Phys. Rev. Lett. 99 182701
[41] Bayman B F and Chen J 1982 Phys. Rev. C 26 1509
[42] Maglione E, Pollarolo G, Vitturi A, Broglia R A and Winther A 1985 Phys. Lett. B 162 59
[43] Stefanini A M et al 2007 Phys. Rev. C 76 014610