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Transfer reactions near the Coulomb barrier*

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Abstract

In this talk I give a brief review of the latest experimental and theoretical developments towards the understanding of the nuclear surface via 'quasi-elastic transfer reactions' which are among the best tools to study the nucleus surface since they are very localized both in energy and in impact parameter. There are also comments on how the discovery and study of the so called "halo" nuclei has changed or confirmed our previous understanding.

The continuous transition towards more complicated reactions like two and multinucleon transfer and fusion is also discussed. Since the problem is still far from being solved I will try to point out the direction for further research, discussing the relative advantages and disadvantages of using reactions with light vs. heavy nuclei and low vs. high beam energies. Special attention is paid to the near to the barrier energies which are the main topic of the conference.

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I. INTRODUCTION

In normal situations nuclei are in the liquid phase because the single particle characteristics of the constituent nucleons are dominant and they are finite because they are made up of neutrons and protons, the latter being subject to the Coulomb force. Their quantum mechanical nature is expressed by the fact that we need wave functions to describe them and these wave functions have tails. Evidently they show up best at the nuclear surface which, as a consequence, is diffuse. A proper theoretical definition of the nuclear diffuseness parameter and an experimental method to determine it do not exist and an interesting introduction to the problem can be found in these proceedings, in the talk of Prof. Dobaczewski. On the other hand the nuclear root mean square radius is easily defined in terms of the nuclear or orbital density as $< r^2 >^{1/2} = \int \rho(r) r^2 dr / \int \rho(r) dr$ and it can be calculated once the density is extracted from experimental data.

In spite of about 40 years of study there are still several phenomenological evidences which are not properly understood. For example the nuclear surface becomes relatively sharper increasing the mass number of the nuclei but also increasing the incident energy of the projectile ion in a nucleus-nucleus reaction. The nucleon-nucleon correlations are more important on the surface because of the diminished effect of the Pauli principle, and various phenomena appear which are all somehow related: the effective mass [1], threshold anomaly in the real potential well [2,3], damping of the single particle resonances [4,5], the role of pairing and surface deformation [6] etc. Finally there is some evidence that for nuclei with $N > Z$ the neutron density function constructed from the single particle wave functions has a larger extension than the proton density such that protons are confined in a smaller volume. The nuclear periphery can be studied with sophisticated methods like antiproton absorption, see Lubinski et al. [7], or electroscattering , see Batty et al. [8]. Here I will concentrate on methods based on nucleon transfer reactions. For a general and very extensive review of the experimental techniques I refer to Rehm [9].

II. SEMICLASSICAL METHODS FOR TRANSFER REACTIONS

In a nuclear collision there is a region of impact parameters in which a transition is made between a condition of no interaction and one in which a strong interaction occurs. In this surface region, where the nucleon density falls down more or less steeply, there is an appreciable probability that a projectile can interact inelastically with one or few target nucleons or just one simple mode of nuclear excitation as the shape oscillations. Then the residual particle escapes. These reactions occur *quickly* because their characteristic times are of the order of the transit time of the projectile across the target. This is comparable with the time it takes a nucleon to complete an orbit . These kind of processes are often well described by perturbation theory and they are called "direct reactions" as opposed to compound nucleus reactions in which particles penetrate deeper and suffer many collisions. Therefore direct reactions constitute a kind of "doorways" through which compound nucleus formation is initiated. For the same reasons they are classified as "quasi-elastic" reactions [9,10].

The description of nuclear reactions is complicated because the quantum mechanical nature of nuclei influences both the relative motion as well as the exchanges of particles, energy, momentum and angular momentum between the interacting ions. However at energies well below or well above the Coulomb barrier and for sufficiently heavy ions the conditions for *semiclassical motion* are satisfied. This happens when the nuclear interaction is not much active and the scattering is governed by the Coulomb field. Then the relative motion is given by a classical trajectory and there is a one by one correspondence between the scattering angle and the distance of closest approach [11]. The trajectories for which there is little overlap of the potentials of the two interacting nuclei give rise to quasi-elastic scattering while those corresponding to strong overlap give rise to strong absorption into many different channels. Broglia and Winther [12] and Esbensen, Broglia and Winther [13] have shown, starting from the full coupled equation solution of the ion-ion scattering, that the transfer probabilities are small enough to be treated as first order perturbation of the elastic ion-ion channel, provided one takes distant trajectories for which the no-overlap condition for the two ion potentials is satisfied. Then the ejectile angular distribution following transfer can be written as

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_R P_{tr}(d) P_{el}(d) \tag{2.1}$$

where $\frac{d\sigma}{d\Omega}_R$ is the Rutherford angular distribution.

The term P_{el} measures the degree of inelasticity along the trajectory if there are absorption effects into other channels [14,15]. The quantity d is the distance of closest approach for the classical relative motion trajectory. A simple strong absorption model supposes that there is a value of the distance of closest approach, called strong absorption radius, R_s, such that $P_{el} = 1$ if $d \geq R_s$ $P_{el} = 0$ if $d < R_s$ where d can be parameterized as

$$d = d_0(A_t^{1/3} + A_{pc}^{1/3}) fm. \tag{2.2}$$

where A_t and A_{pc} are the mass numbers of the target and projectile core. A smooth cut-off parameterization which takes into account the surface diffuseness has been introduced in [16] as

$$P_{el}(d) = exp(-(ln2)exp(R_s - d)/a) \tag{2.3}$$

where a is a surface diffuseness parameter which could be derived by fitting the above equation to data of the type shown in Fig.(1) and discussed in the following and R_s is defined by $P_{el}(R_s) = \frac{1}{2}$. Eq.(2.3) originates from the semiclassical forms of the nuclear nucleus-nucleus S-matrix and phase shift which can be related to the imaginary part of the ion-ion optical potential [14,15].

Therefore the first problem is to find the value of the parameter d_0 such that $d = R_s$, thus defining somehow the borderline between elastic and absorptive channels. The value of R_s is important also because it is the radius which enters into the definition of the nominal Coulomb barrier. In very heavy systems, due to strong deformation R_s cannot have an unique value. In the same way when several steps occur during the reaction leading to different deformations, various barriers will be present at each different step. The complexity in the unique definition of d_0 can be seen in Fig.(1) from Rehm [17], where the ratio of the quasielastic cross section to the Rutherford one is given as a function of d_0 for heavy (top) and light systems (bottom). One sees clearly that it is necessary to go to large relative distances in order to attain the regime of pure classical elastic scattering and that there is a certain spread of cross section values in the case of light systems. Therefore stronger nuclear structure effects are expected at the surface of light nuclei as compared to the case of heavy nuclei because there is an extended region of small but not negligible overlap between the two potentials. The same information can be drawn from Figs.(2a) and (2b) which show systematics of one neutron transfer reactions as a function of the ground state Q-value for energies well above the Coulomb barrier (a) [18] and close to it (b) [19].

The success of the smooth systematics indicates that aside of the Q-value and separation-energy dependence, nuclear structure is essentially averaged out when integrated cross sections are considered for high incident energies. In the case of Fig. (2b) the points for light systems show a large spread which in our opinion indicates again that for light systems the structure of the surface change so much from system to system that an average description cannot be attained [20].

III. ONE-NUCLEON TRANSFER

Once that the semiclassical conditions for the scattering are realized, the next step is to determine the form of the transfer probability or form factor given by the factor P_{tr} in Eq.(2.1). Experiments can measure the transfer and elastic cross sections. Then von Oertzen and several other authors ([21] and references therein) plot the ratio σ_{tr}/σ_{el} as a function of the parameter d_0. At very large distances where Eq.(2.1) and $P_{el} = 1$ should hold, and in presence of only, hopefully, transfer channels, the result on a logarithmic scale is a straight line suggesting that $P_{tr} = e^{-2\alpha d}$. The exponential dependence on d is easily understood on the basis of the tunnelling interpretation of the transfer process. An equivalent physical interpretation in terms of the overlap between initial and final neutron momentum distributions can also be found in Lo Monaco and Brink [22].

For all systems the values of the one-nucleon transfer probability P_{1n} obtained are in the range 0.1-0.2 at an overlap parameter $d_0 = 1.5$fm , a fact which shows that the integrated single particle strength (nuclear density) outside a given nuclear radius does not vary significantly with the mass of the nucleus. This statement refers to processes, where nucleons are exchanged between their low-lying configurations at the Fermi surface, which is generally the case at energies below the barrier [23].

The exponential form of the transfer probability obtained from phenomenological evidence is often referred to as the Bass model [11] at energies below the barrier and the decay slope is given as $\alpha^2 = -2m\tilde{\varepsilon}/\hbar^2$ with

$\tilde{\varepsilon} = (\varepsilon_i\varepsilon_f)^{1/2}$. The model of Brink and collaborators valid at high energy assumes that the relative motion trajectory is a straight line, then a proper quantum mechanical calculation of the transfer probability gives also an exponential behavior [16,22] and the following form of the averaged energy used to define the slope parameter:

$$\tilde{\varepsilon} = \frac{1}{2}(\varepsilon_i + \varepsilon_f) - \frac{1}{4}\left(\frac{(\varepsilon_i - \varepsilon_f)^2}{\frac{1}{2}mv^2} + \frac{1}{2}mv^2\right) \tag{3.1}$$

where $\frac{1}{2}mv^2$ is the incident energy per nucleon at the distance of closest approach $d = R_s$ and ε_i, ε_f are the initial and final binding energies of the transferred nucleon, respectively.

The approach of Sørensen and Winther [24] is similar in spirit to the Brink model but it is valid at energies close to the barrier because it takes into account acceleration effects along the trajectory of relative motion. It gives also an exponential form of the transfer probability, with a slope definition a bit more complicated than Eq.(3.1). These authors have shown that the two methods are of comparable accuracy starting from energies of about $2V_{CB}$.

The formula (3.1) implies that the slope parameter is a function of the incident energy. It has a minimum when $|Q| = |\varepsilon_i - \varepsilon_f| = \frac{1}{2}mv^2$. Fig.(3) from Ref. [17] shows that α, as function of E_{inc}, has a behavior close to the one predicted by Eq.(3.1). Then the exponential form of the transfer probability implies that, at high incident energies the cross section is maximum in correspondence to the minimum value of the slope parameter α. At energies close to the barrier one should have $Q = 0$ in order to have the optimum transfer conditions, while at energies below the barrier the most favorite reactions have $Q > 0$.

Several types of slope anomalies are discussed in the literature whenever the data do not fit the above picture of an exponential probability decaying with a simply defined parameter. Same examples are:

- the experimental slope parameter is not consistent with the predictions (e.g. for 2n transfers or for deformed nuclei, see next section);

- there are oscillations in the differential cross section;

- the slope decreases with increase of energy from below the barrier to values close to it [25] or strongly increases with increasing of energy [26];

- the ratio between 2p and 1p transfers is strongly energy dependent [26].

A discussion of these effects can be found in a recent review paper [21]. Some authors suggest that the anomalies can came from the fact that the exponential form factor and/or Eq.(2.1) do not apply. This can be due to coupling with other channels and/or to diffraction effects which invalidate the simple picture of scattering along a Rutherford orbit. In some cases the slope parameter has to be defined better, for example for energies well above the barrier one should use Eq.(3.1) which, as discussed above, takes into account the incident energy dependence. In some cases improvements in the understanding have been obtained by

a) extending the semiclassical model by taking into account the (usually disregarded) influence of the nuclear branch of the deflection function [26–31], or by

b) introducing quantum diffractional effects [31–34].

Traditionally transfer reactions are used for determination of spectroscopic factors. This can be obtained when transitions to individual levels are resolved and comparison with standard DWBA calculations of angular distributions is made. Typical examples are shown in Fig. (12) of Rehm [9] review paper. Experimental absolute cross sections for one-neutron transfer can be used to get asymptotic normalization constants [16,22,35] by comparing to calculations which use microscopic form factors obtained using analytical solutions of the Schrödinger equation outside the nuclear potential well [35]. From this information and the experimentally known binding energy one can deduce the "true" wave function, the Wood-Saxon well parameters and finally calculate the mean square radius . Some papers on this subject are those of J.L.Durrel et al. [36] and Körner and Schiffer [37]. In particular in the latter [37] the (d,t) and (p,d) reactions on ^{208}Pb have been studied at several energies below the Coulomb barrier. Relatively simple and parameter-free analysis yields the absolute normalization of the asymptotic tail for the neutron states near the Fermi surface. We show in Fig.(4) from [37] the density distributions obtained for neutrons and protons and the Tables I and II which give the root mean square radius for several single particle orbits as well as the rms radii of the proton and neutron distributions. Fig.(4) is one of the best evidences that in presence of a neutron excess, the neutron density extends further out than the proton density.

There are however other, and perhaps better probes of the nuclear periphery as low energy negative hadrons, like K and $\overline{p}$ [8]. E.g. the paper [38] shows that $\overline{p}$ are absorbed in a region around $3fm$ beyond the half-density radius. This is caused by the short mean free path of $\overline{p}$ in nuclear matter, which is shorter than $1fm$, as well as the mechanism of interaction via atomic cascade which populates states of high angular momenta.

Another interesting point to be discussed is the excitation energy sharing between the direct reaction partners which has been studied since many years, however experimental data are very scanty. The few available data, e.g. Ref. [39,40] suggest that the excitation energy is transferred mainly towards the receptor, a direction preferred also by the semi-classical model of Brink and collaborators [22]. Some new insight into the problem has been recently obtained by using the particle-gamma coincidence methods. Wu et al. [41] have found that at least in 1n transfer between ^{161}Dy and ^{58,61}Ni at near barrier energies the receptor receives substantial fraction of the total excitation. The theoretical interpretation of experimentally found partition of excitation energy suggests that it is determined mainly by spectroscopic factor distribution. The new generation of gamma-ray detectors capable of effective measurements of gamma-gamma correlations between the donor and receptor is giving exciting new possibilities to study this problem.

IV. TWO-NUCLEON TRANSFER

As we have shown before one nucleon transfer is a useful tool to obtain spectroscopic information. Two nucleon transfer is important to understand pairing which is the basic clustering phenomenon in nuclei. In particular it is important to understand whether pair transfer is a two-step or one-step process. In fact if nucleons are transferred independently of each other in successive steps, it means that the shell effects are dominant. The transfer probability should decay, as a function of the distance of closest approach d, with a slope 2α where the parameter α has been already discussed in the previous section. This expectation is very seldom met by the experimental data which in most cases follow a less steep decay. Such an enhanced behavior is often interpreted as an evidence for one-step pair transfer [21]. Simultaneous pair transfer is a measure of the configuration mixing between several single particle wave functions necessary to build up the pair wave function [42]. Configuration mixing has to be complete if pairing is the dominant structure effect on the surface. Experimentally these studies are very demanding: one needs good mass, charge and Q-resolution at the same time. Also the cross sections are small and need to be measured with great accuracy, for this reason spectrometers are the best detection systems for such reactions. However the obtained results are quite rewarding.

Two recent experiments suggest dominant [43] or at least important [21] role played by simultaneous pair transfer mechanism. In both cases medium-heavy ions were used (^{58}Ni+^{60,64}Ni in the former and ^{37}Cl+^{40}Ca in the latter) et energy close to the barrier. Fig.(5) from [43] shows the ratio of the quasi-elastic angular distribution to the Rutherford one for several incident energies. At backward angles it is bell shaped at the highest available energy and the data can be explained including the coupling to pair transfer by using macroscopic form factors as in Dasso and Pollarolo [44]. A similar result is illustrated by Fig.(6) from von Oertzen [21], where the data from one-proton transfer ^{40}Ca(^{37}Cl,^{38}Ar)^{39}K are plotted together with those for two-proton transfer in ^{40}Ca(^{37}Cl,^{39}K)^{38}Ar, as populating the same final channel with ejectile and recoil interchanged [45].

However, experimental data on this subject are still rare (the elastic 2n transfer was observed [43] in quite a heavy system for the first time) and the above findings cannot be generalized, since they are certainly system dependent. E.g. the authors of [43] noticed that the pair deformation parameter which measures the collective character of the pair transfer mode increased with the valence neutron number.

To conclude this section I would say that theoretical results are in most cases in qualitative agreement with experimental results but there is still a lot to do. For example experiments have not been able so far to distinguish sequential transfer from pair transfer. From the theoretical point of view often one supposes that the transfers of individual nucleons are independent of each other and the Q-value effects are averaged somehow. In the case of simultaneous pair transfer effective form factors are used but we still lack a microscopic theory of pair transfer. Some insight in the problem could come from the understanding of the breakup of halo nuclei like ^{11}Li and ^{6}He. Both of them have two neutrons in the halo, but apparently their breakup and fusion properties are different. I will come back to this subject in the section on halo nuclei.

V. MULTINUCLEON TRANSFER

Many features of multinucleon transfer are still very poorly understood, as e.g. the relative weight of sequential transfers to the more complicated ones involving transfer of pairs or nucleon clusters [46]. The latest results on multinucleon transfer are from Jiang et al. [47] and Corradi et al. [46] . They measured respectively the systems $^{58}Ni +^{124} Sn$ and $^{48}Ca +^{124} Sn$. In the first case the transfer of up to six neutrons was studied while the second experiment measured up to six-proton transfer. In both cases it was necessary to make full coupled channel calculations to explain the data. Here I show in Fig. (7) from [46] the mass distribution of the ejectile nucleus corresponding to only neutron transfer (0p) or to neutron transfer plus 1p and 2p stripping and pickup. The histogram presents the calculations according to the model of Winther [48] which takes into account only successive transfer. Pair transfer and the important α transfer are taken into account in the calculations shown in the lower part of Fig.(7) where one can see that the accord with the experimental data has improved. Both experiments find that the centroid of Q-value spectra move towards higher excitation energy and the widths increase as the number of transferred neutrons increase. These features could not be reproduced by the calculations.

Multinucleon transfer and the fact that the transfer can be sequential or simultaneous show the interplay between structure and reaction mechanism. Increasing the number of particles transferred one increases the interaction time and then the inelasticity of the reaction. There is neck formation and the dynamics evolves towards fusion, passing trough a deep inelastic stage. Such a regime is discussed by Prof. Volkov contribution to this conference. Several interesting papers on the subject of transfer as a doorway to fusion can be found in [49]. Obviously such an evolution must correspond also to a change in incident energy to meet the best experimental conditions to obtain large cross sections. Spectroscopy with light nuclei is best done at low energy but with heavy ions one needs to go at energies of several tens of MeV. On the other hand coupling of transfer to other degrees of freedom is best done at low energies, around the barrier.

VI. COUPLING TO OTHER CHANNELS

An important difference between heavy ion induced reactions and the light-ion collisions is the increased importance of the coupling between the various reaction modes. I discuss now briefly the coupling between transfer and other channels, in particular inelastic excitations and fusion. In such a coupling regime, which is quite common at energies near the barrier, transfer is most often a doorway to fusion so it is interesting to study which of the two is most important and in which conditions. The main dependence is probably on the masses and shell structure of the two nuclei and on the Q-values involved. In most cases these couplings act as to decrease the effective barrier and so fusion is enhanced.

For example the work of Vandenbosh et al., [50] has shown that fusion and quasi elastic excitation functions measured for the quasi-symmetric system $^{40}Ca +^{46,48,50} Ti$ at several incident energies near the barrier , $E_{inc} = 100 - 150 MeV$, can be explained only introducing coupling to 1 and 2-neutron transfers and to surface vibrations. In particular for the above system transfer coupling rises with target mass number. This is because the Q-value becomes more positive, what enhances transfer probability, and at the same time the probability of surface vibrations diminishes approaching shell closure.

The recent results of the coupled-channel analysis [51] of the ^{58}Ni+^{124}Sn reaction [47] show the degree of maturity reached by theory: they provide a comprehensive and fairly consistent description of not only the one- and two-neutron transfer data, but they also reproduce the sum of measured fusion and deep-inelastic collision cross sections.

One should mention also that in the case of heavy nuclei transfer often happens from and to Coulomb excited states. Such a process is best studied using γ-ray experiments like the ones performed by the Rochester group [41] and described in Prof. Cline talk in these proceedings.

Finally I discuss in the next section halo nuclei.

VII. HALO NUCLEI

In the last ten years since the advent of Radioactive Beams (RIBs) [52] a new phenomenon called 'nuclear halo' [53] has appeared in nuclear physics. There is a halo on a nucleus (Ex: ^{11}Be) when the last neutron or the last couple of neutrons, as in ^{11}Li or ^{6}He, are very weakly bound ($\varepsilon \approx -0.1MeV$) and in a single particle state of low angular momentum (s or p). Then the single particle wave function has a long tail which extends mostly outside the potential well. Because of these characteristics the reactions initiated by such nuclei give large cross sections for neutron breakup, a reaction in which a neutron is transferred not to a bound state of the acceptor but rather to continuum final states (i.e. ejected). Also the ejectile parallel momentum distributions following breakup are very narrow, typically $40 - 45MeV/c$, which is related to the large spatial extension of the halo nuclei *via* the uncertainty principle. There are also some candidates for a proton halo, like ^8B [54–56]. But because of the Coulomb barrier which keeps the wave function localized at the interior, there is still not a clear experimental evidence for this phenomenon. More recently another radioactive nucleus ^{19}C has been produced [57] but there also the presence of a halo has not been unambiguously proved yet.

Then halo nuclei seem to be the ideal candidates for the study of the nuclear periphery characteristics. What is accepted by now is that the halo is a property of the single particle state which is near the particle emission threshold so that even if its binding energy is still negative, a large part of its strength is already in the continuum. The reactions studied so far are mainly of the breakup type at high energy ($E_{inc} \approx 40MeV/u$). In such a situation the formalism of Eq.(2.1) applies with the transfer probability substituted by the breakup probability [58]. The latter has still an exponential behavior related to the neutron momentum distribution in the initial state. Therefore such reactions can give the same type of information as the transfer reactions. Furthermore, while transfer between normal nuclei gives information only on one value of the momentum distribution of the neutron in each of the two interacting nuclei [16,22], it is only when breakup occurs that thanks to the continuum distribution of final energies, the full momentum distribution in the initial state can be studied.

The "normal" matching condition near the barrier $Q = 0$, discussed in Section III, would clearly be difficult to realize because of the small initial binding, unless the projectile-core and target are the same, as discussed in [59] for example. In most of the cases it will be $Q > 0$. Also various transfers to excited states will perhaps be possible. Suggestions about transfer with weakly bound nuclei have recently been made in [60,61].

The lowest incident energies accessible will probably be in the LNS in Catania with the project EXCYT [62] and it will be of the order of 3-10MeV/u. For Li this means $E_{inc} = 33 - 110MeV$ which corresponds to near the Coulomb barrier for a target nucleus like Pb ($V_{CB} \approx 36MeV$). Then the matching condition $|Q| \approx mv^2/2$ will be realistic giving as most favorite final energy a positive value of the order of $\varepsilon_f = 10MeV$. It is well known that there is a group of resonances in that positive energy range ($2h_{11/2}$, $1k_{17/2}$, and $1j_{13/2}$) in lead and they could be in principle populated by transfer. The same could be done on lighter targets like ^{90}Zr or ^{40}Ca . These will be *very* difficult experiments, because of the low beam intensities and because of the competition with Coulomb breakup. It appears then as if reactions mechanisms typical of the regime of "high energy" for normal nuclei could dominate also when "low energy " beams of weakly bound projectiles will be used. I have estimated the one-neutron transfer cross section vs. breakup for the system ^{11}Be $+^9Be$ for which the ground state-ground state Q-value is $Q = 6.3MeV$. At $E_{inc} = 3MeV/u$ ($V_{CB} \approx 3.7MeV$) I find a transfer cross section $\sigma_t = 5.5mb$ vs. a breakup cross section $\sigma_b = 355mb$.

Another interesting question is whether the breakup channels would diminish or increase the fusion probability . Experiments performed at Riken by Petrascu et al. [63] and at Ganil by Fekou-Youmbi et al., [64] do not give any clear evidence. In Fig.(8) I show the results for the fusion of ^{11}Be and ^{9}Be with ^{238}U [64] as a function of the incident energy. Actually it seems that ^{11}Li and ^{9}Li give the same fusion cross sections. In ^{11}Li the s and p states forming the 2-neutron halo have a very strong overlap which makes them decay simultaneously into the continuum in breakup reactions. On the other hand there are clear evidences that in ^{6}He breakup the first neutron breaks up immediately while the other decays in flight going through the excitation of a resonance, the $1p_{3/2}$ ground state of ^{5}He which has an estimated width of $\Gamma = 600keV$ according to Aleksandrov et al. [65]. Also there is some evidence that fusion initiated by ^{6}He is enhanced with respect to ^{4}He [66].

From the point of view of theoretical calculations, von Oertzen and Krouglov [67] use standard coupled channel calculations to show that fusion will be inhibited. However one should mention that coupled channel codes do not treat breakup properly because they do not have the proper form factor and because they cannot have the proper optical potential which is still unknown. Takahashi et al. [68] make an argument based on the dependence on the separation energy which seems very convincing and they conclude that fusion will not be enhanced, actually they find up to 40% reduction at high energy. Dasso and Vitturi [69] leave the problem open.

A very good discussion can be found in Signorini [70] and Thompson [71] talks at the Fusion 97 conference. Thompson makes a clear argument about the interpretation of the mechanism of breakup. If it goes trough some sort of inelastic excitation in the projectile then being somehow reversible it could enhance fusion (see Imanishi and von Oertzen [59]), otherwise a pure three body breakup would inhibit fusion. The competition between inelastic low-lying excitations in the projectile and transfer to target states is a long-standing problem in the study nuclear reaction mechanism, since the paper of Bertsch and Shaeffer [72]. In fact the two situations could be complementary and most relevant at low and high energy respectively. Clearly the structure of the initial nucleus is also very important.

VIII. CONCLUSIONS

I would like to conclude this paper by saying that due to the space-time limitations I am not able to discuss several interesting subjects as multistep processes and their interference with one-step reactions [9,73], transit to the chaotic reaction regime [73], interference between inelastic scattering and transfer from high-spin states in deformed nuclei [9,74], searching for the nuclear analog of the Josephson effect [9,23,43,74,75], "diabolic points" on nuclear rotational state population in 2n transfer and transition from the superfluid to the normal phase at high angular momentum [74,76], or application of transfer reactions to investigations of the importance of nonzero spin terms in the pairing potential [74], just to name few of them. In the large majority of cases they are open questions, waiting for systematic investigations.

I hope however, to have presented enough evidences for the richness of studies connected with transfer reactions close to the Coulomb barrier. I have tried to show that transfer phenomena are interesting not only from the point of view of the reaction mechanism but that they can actually help in answering (and asking!) questions regarding many important problems of Nuclear Physics. Large advances in our understanding have been made thanks to recently developed theoretical and experimental methods. But as the last section on halo nuclei indicates, many challenging things are still before us !

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Figure captions

Fig.1. Cross sections for quasielastic scattering (including excitation up to 5 MeV) normalized to the corresponding Rutherford value plotted as function of the reduced radius parameter d_o for heavy (a) and light (b) systems [17].

Fig.2. Reduced transfer cross sections, defined as $\sigma_t * (B_i B_f)^{1.1}$ (B_i and B_f being the neutron separation energies in the donor and acceptor nuclei) as a function of the ground-state Q value. The curve is the fit to the data. (a) data corresponding to $20 - 30\%$ above the Coulomb barrier [18]. (b) the same close to the barrier. Full squares: systems with $Z_p Z_t \geq 1800$,open squares: $Z_p Z_t < 1200$, asterisks: intermediate systems [19].

Fig.3. (a) Experimental slope parameters 2α for the one-neutron transfer reaction ^{208}Pb(^{58}Ni,^{59}Ni)^{207}Pb as a function of the energy above the Coulomb barrier E/V_{CB}. The dotted line is the theoretical slope calculated according to the Bass model. (b) The same, but for the two-neutron transfer ^{208}Pb(^{58}Ni,^{60}Ni)^{206}Pb [17].

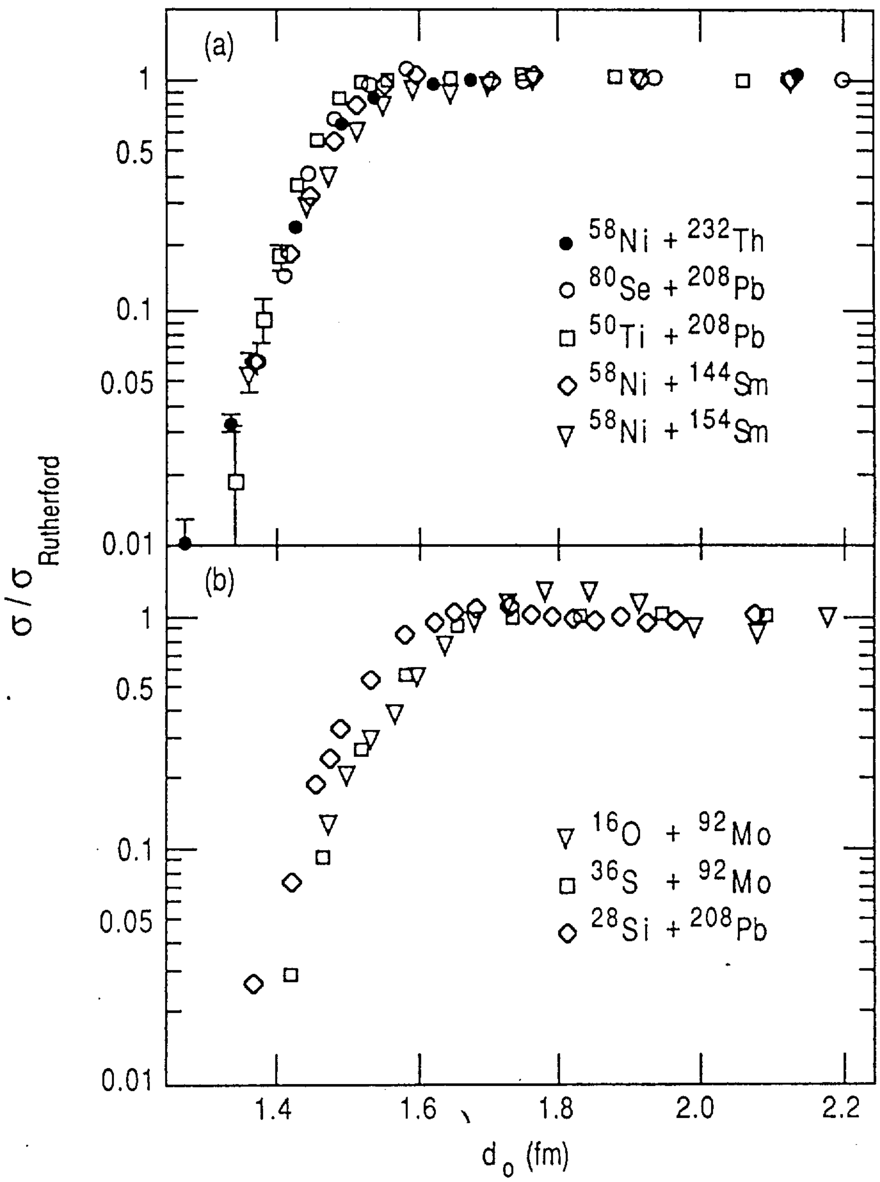
Fig.4. Neutron and proton densities in ^{208}Pb derived from the 1n transfer data [37].

Fig.5. Elastic scattering angular distributions of ^{58}Ni+^{60}Ni. The solid lines are the results of the CC calculations including the first-order couplings to inelastic excitations of collective 2_1^+ and 3_1^- states of both projectile and target. The dashed lines are the results including the pair transfer process [43].

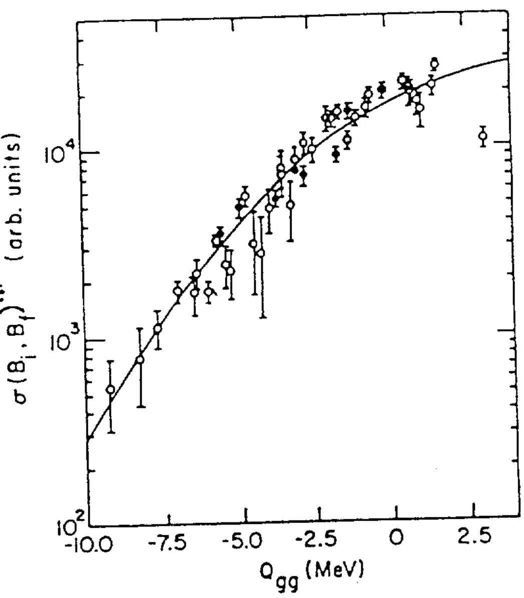
Fig.6. Angular distribution of $^{27}Cl +^{40} Ca \rightarrow^{39} K +^{38} Ar$. The curves correspond to different variants of calculations. In particular solid line is the result of calculations including both single-step and sequential pair transfer processes [21].

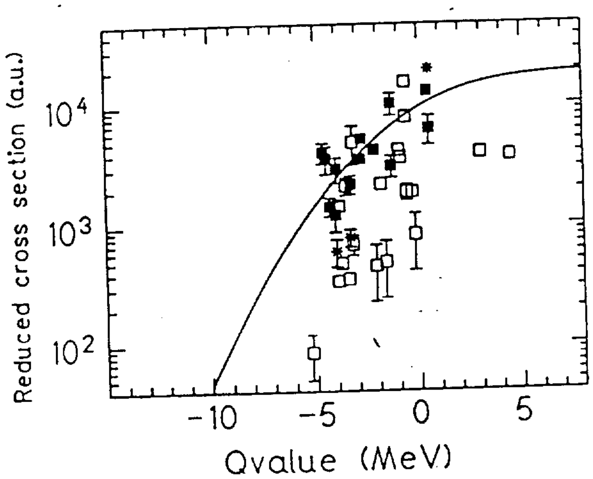
Fig.7. Experimental (points) and calculated (histograms) angle integrated cross sections for the transfer products. The lower part of the figure shows the results of taking into account in the calculations pair nucleon transfer and α transfer processes [46].

Fig.8. Fission cross section for ^{9,11}Be+^{238}U as a function of the ratio E_{cm}/V_{CB}. The line corresponds to the coupled-channels calculation for ^{9}Be+^{238}U reaction [64].

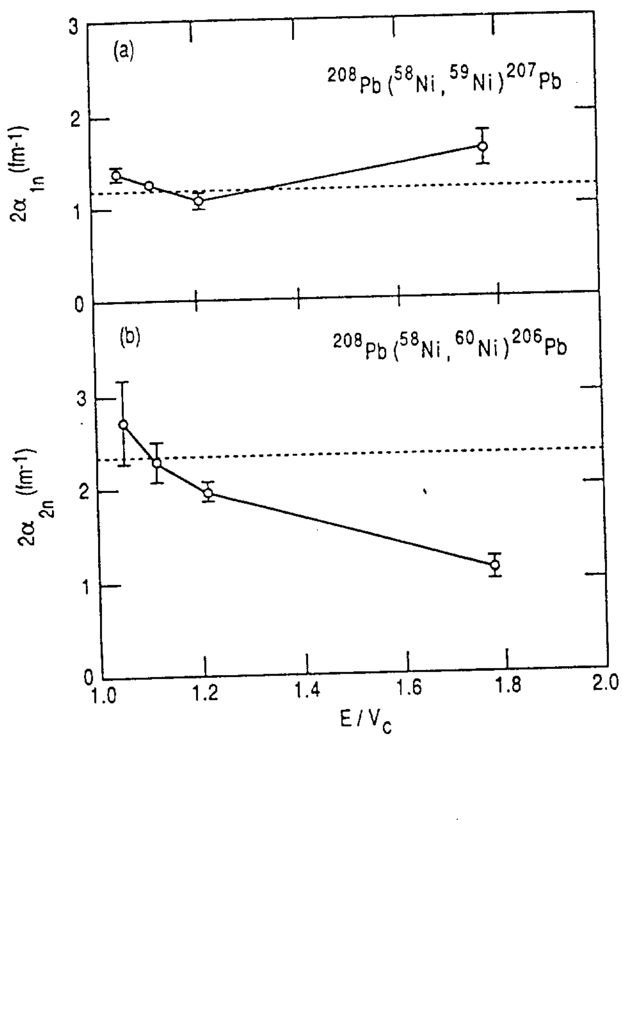


(a)
(b)
1
0.5
0.1
0.05
0.01
^{58}Ni + ^{232}Th
^{80}Se + ^{208}Pb
^{50}Ti + ^{208}Pb
^{58}Ni + ^{144}Sm
^{58}Ni + ^{154}Sm
^{16}O + ^{92}Mo
^{36}S + ^{92}Mo
^{28}Si + ^{208}Pb
σ / σ$_{Rutherford}$
1.4
1.6
1.8
2.0
2.2
d$_o$ (fm)





A. Bonaccorso (2)



A. Bonaccorso (3)

TABLE I Mean-square radii.

State	$\langle r^2 \rangle^{1/2}$ [a] (fm)
$3p_{1/2}$	6.10 ± 0.10
$3p_{3/2}$	5.97 ± 0.09
$2f_{5/2}$	5.92 ± 0.05
$2f_{7/2}$	5.76 ± 0.05
$1i_{13/2}$	6.20 ± 0.15
$1h_{9/2}$	5.90 ± 0.15 [b]
Average [c]	5.99 ± 0.10

[a] The uncertainties reflect both experimental errors and some of the uncertainties in the wave functions used to estimate $\langle r^2 \rangle$ from the magnitude of the tail.

[b] Not directly from data, but estimated by extrapolating from the $p_{1/2}$ and $f_{5/2}$ states using a variety of Woods-Saxon potentials.

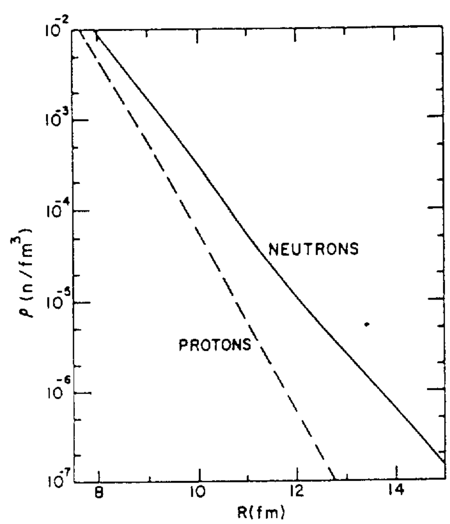
[c] Weighted by the number of particles in each orbit.

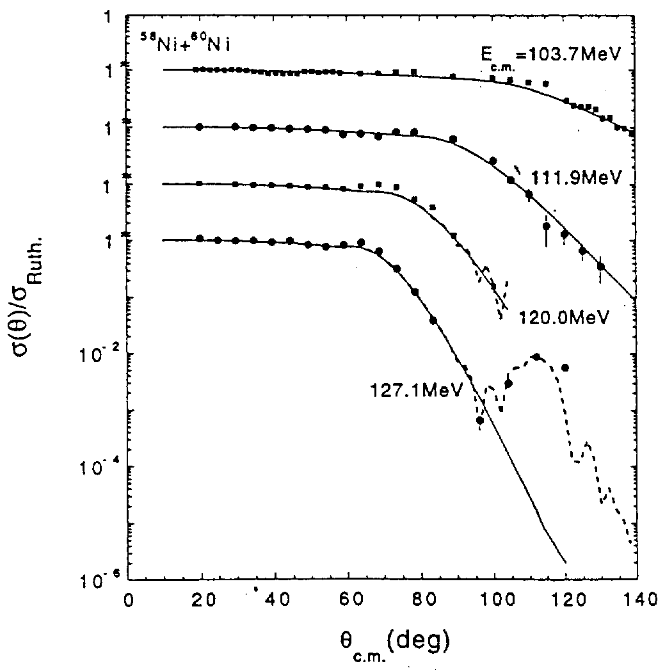
TABLE II Summary of root-mean-square radii[a]

	$\langle r^2 \rangle^{1/2}$ (fm)
Protons (charge)	5.51
Neutron excess (from Coulomb energy difference)	5.95
Neutron excess (from present work)	6.04 ± 0.10
Neutron excess (predicted from Woods-Saxon well)	6.28

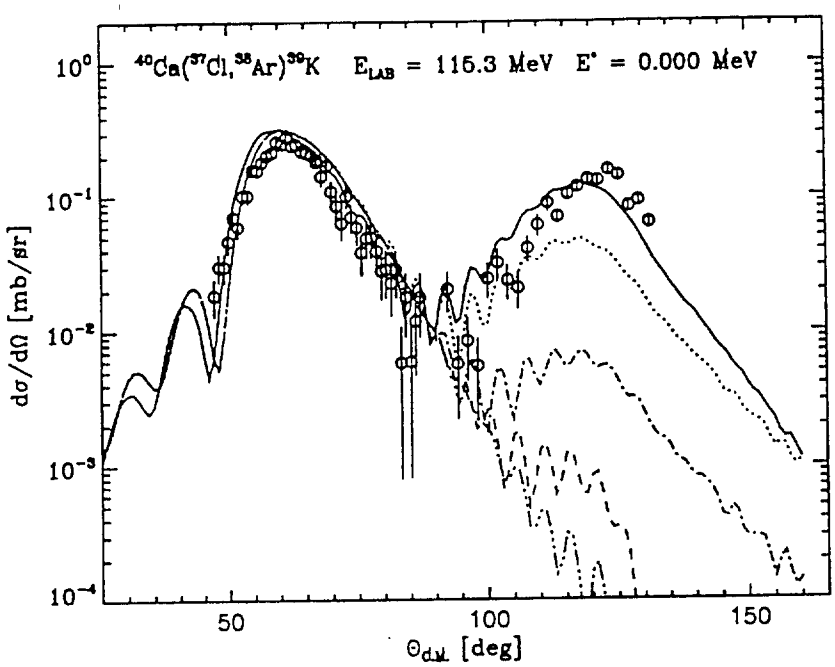
[a] For purposes of comparison with the charge radius, the finite size of the nucleon is folded into the radii.

A. Bonaccorso

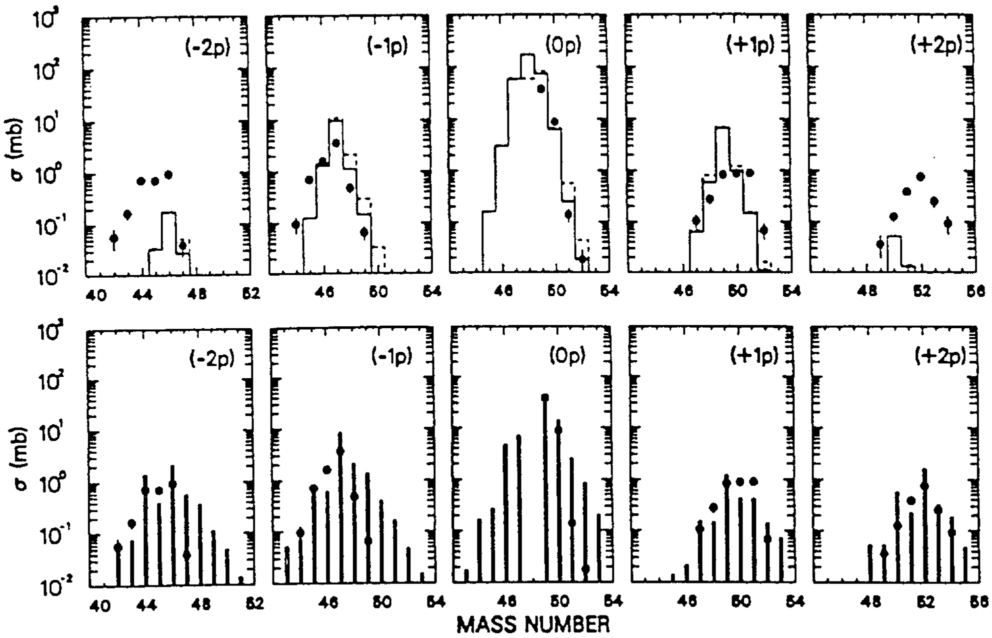


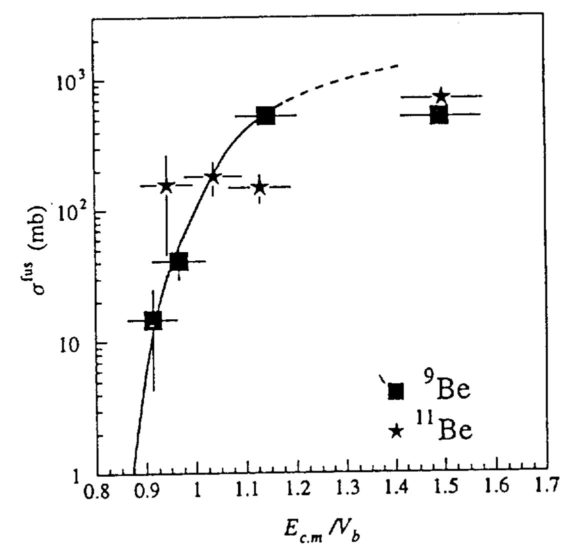


(4) A. Bourgogno (5)



A. Bonaccorso (6





A, Bonaccorso

(8)