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Probing nucleon-nucleon correlations via heavy ion transfer reactions

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Abstract. The revival of transfer reaction studies benefited from the construction of the new generation large solid angle spectrometers, coupled to large γ arrays. The recent results of γ-particle coincident measurements demonstrate a strong interplay between single-particle and collective degrees of freedom that is pertinent to the reaction dynamics. By studies of transfer of pairs, valuable information on the component responsible for particle correlations has been derived.

1 Introduction

Transfer reactions have an important impact in the understanding of correlations in the nuclear medium, and play a very important role for the study of the evolution from the quasi-elastic to the deep-inelastic and fusion regime [1]. In heavy-ion induced transfer reactions, the constituents of the collision may exchange many nucleons, thus providing information on the contribution of single particle and correlated particle transfers, and on the contribution of surface vibrations (bosons) and their coupling with single particles (fermions). The the component responsible for particle correlations such as the pairing interaction can be studied in multinucleon transfer reactions. Although, the analysis and interpretation of these reactions can be quite complex because information about correlations is often hidden in the inclusive character of the extracted cross sections. Making use of the semi-classical approximation it has been possible to extend the concept of elementary modes of excitation in the reaction model that allowed to quantitatively study reactions that involve the transfer of many nucleons, and to predict how the total reaction cross section is shared between different channels.

The recent revival of transfer reaction studies greatly benefited from the construction of the new generation large solid angle spectrometers based on trajectory reconstruction that reached an unprecedented efficiency and selectivity. The coupling of these spectrometers with large γ arrays allowed the identification of individual excited states and their population pattern.

In this paper, some of the main advances in the field recently achieved are outlined. After a brief presentation of the experimental techniques, the main characteristics of multinucleon transfer reaction will be discussed. In particular how single particle and more complex degrees of freedom act in the transfer process.

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2 Heavy ion magnetic spectrometers

Different techniques have been employed to identify nuclei produced in transfer reactions, most of them making use of magnetic spectrographs or spectrometers for a complete identification of nuclear charge, mass and energy of final reaction products. While dealing with heavier ions and weaker transfer channels, the solid angle of spectrometers increased. For such large solid angle spectrometers, in order to preserve nuclear charge and mass separation position information becomes crucial. The presently adopted solution in such cases is a simplified magnetic element configuration and the use of the concept of trajectory reconstruction. This idea has been successfully employed in the very large solid angle (~100 msr) spectrometers PRISMA [2, 3], VAMOS [4] and MAGNEX [5].

As an example of the performance of these large solid angle spectrometers, in Fig. 1 is shown the mass distribution of chlorine isotopes populated in ^{40}Ar+^{208}Pb reaction measured with the spectrometer PRISMA. As the energy resolution is presently limited to few hundreds of keV, the spectrometers have been coupled with large γ arrays (CLARA [6], AGATA [7], EXOGAM [8]) in order to distinguish the excited states of the final fragments. The quality of the γ array spectra, obtained after Doppler correction based on the knowledge of the velocity vector measured in PRISMA, is also demonstrated in Fig. 1 (bottom).

A very important use of such γ-particle coincidence technique is for studies of nuclei moderately far from stability whose structure is poorly known (see for example [9, 10] and refs. therein). At variance with reactions (like fusion evaporation) where the γ cascade proceeds from high-level density regions and ends-up in yrast states, grazing reactions favor a certain degree of direct population of final states, and facilitates the study of states associated with specific excitation energy or with specific structural properties.

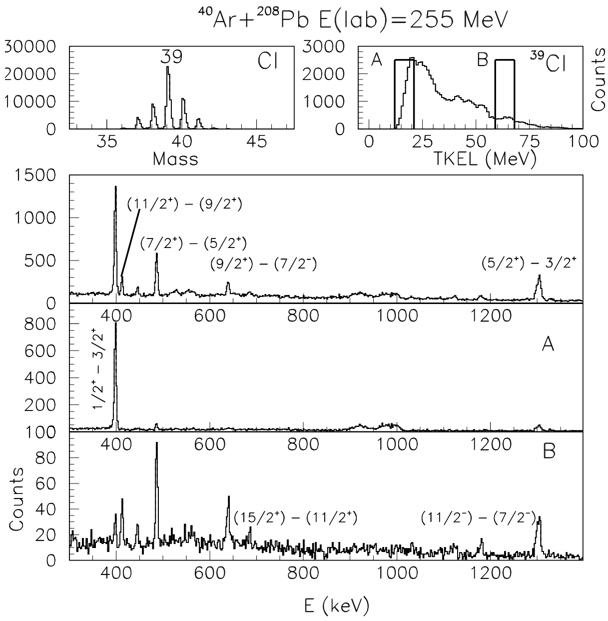

Figure 1. (Top left) Mass distribution of chlorine isotopes populated in ^{40}Ar+^{208}Pb at $E_{\rm lab}$ = 255 MeV and at $\theta_{\rm lab}$ = 54° in coincidence with γ rays. (Top right) TKEL distribution for ^{39}Cl ($-1p$ channel) produced in the ^{40}Ar+^{208}Pb reaction. (Bottom) Associated γ-ray spectra for ^{39}Cl without conditions on TKEL (top) and conditioned (middle and bottom) with different regions of TKEL distributions, marked as (A) and (B) in the TKEL spectrum.

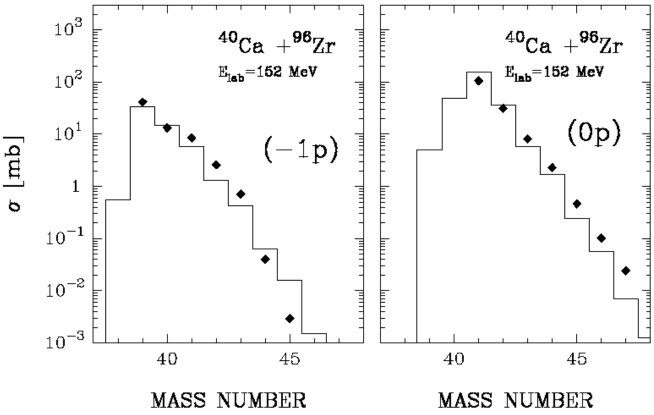

Figure 2. Total cross sections for one-proton stripping (left panel) and pure neutron pick-up (right panel) channels in the ^{40}Ca+^{96}Zr reaction. The points are the experimental data and the histograms are the GRAZING code calculations (see text).

3 Reaction mechanism

Grazing collisions produce a wealth of nuclei in a wide energy and angular range and with cross sections spanning several orders of magnitude. The determination of the absolute cross sections was crucial in order to understand how the total cross sections is divided between many open channels, and which degrees of freedom govern these processes. The quality of data and theoretical calculations presently achieved is demonstrated in Fig. 2 where it is shown, as a representative example, the neutron pick-up channels and the channels involving the one proton stripping ($-1p \pm xn$) in the reaction ^{40}Ca+^{96}Zr [2].

The total cross sections in Fig. 2 are compared with calculations performed with the semi-classical code GRAZING [11]. This model calculates how the total reaction cross section is distributed amongst the different reaction channels by treating quasi-elastic and deep-inelastic processes on the same footing. The GRAZING model takes into account, besides the relative motion variables, the intrinsic degrees of freedom of projectile and target. These are the surface degrees of freedom and particle transfer. The exchange of many nucleons proceeds via a multi-step mechanism of single nucleons.

The total cross sections on the multinucleon transfer reactions have been also recently studied within the model based on Langevin [12] or Time Dependent Hartree Fock theory [13–15].

Total angle and Q-value integrated cross sections for multi-neutron and multi-proton channels have been investigated with spectrometers in various systems close to the Coulomb barrier (^{58}Ni+^{208}Pb [16], ^{40}Ca+^{208}Pb [17, 18], ^{40}Ca+^{96}Zr, ^{90}Zr+^{208}Pb [2, 19], and ^{40}Ar+^{208}Pb [20]). In these systems one finds that most nuclei produced in transfer reactions have N/Z ratio smaller than one of the compound nucleus, implying the dominance of a direct mechanism in the population of different fragments. For the many-proton transfer channels the isotopic distributions drift toward lower masses, a clear indication that these distributions are affected by evaporation processes. The cross sections for the neutron pick-up drop by almost a constant factor for each transferred neutron, as an independent particle mechanism would suggest. The comparison with calculations supports this idea. One can also mention that the pure proton cross sections behave differently, with the population of the ($-2p$) channel as strong as the ($-1p$) channel, suggesting the contribution of processes involving the transfer of proton pairs in addition to the successive transfer of single protons. This apparent proton and neutron asymmetric behavior is due to the fact that the one-neutron transfer cross section is almost one order of magnitude larger than the one-proton transfer (see Fig. 2). Thus, the contribution of a pair-transfer mode is masked, in the neutron sector, by the successive mechanism. As the very short-range pairing interaction redistributes the strength around the pure configurations, it is very important to study the yields distribution of the individual states. This subject will be addressed in next section.

4 Nucleon-nucleon correlations

Heavy-ion transfer reactions are an ideal tool for the study of the residual interaction in nuclei, in particular the components responsible for the couplings between the single particle and phonon degrees of freedom, as well as particle correlations. Below, the recent studies on the subjects will be discussed.

4.1 Particle vibration couplings

The coupling of single-particle degrees of freedom to nuclear vibration quanta is essential for the description of many basic states in the vicinity of closed shells. The effects of such coupling are largely unexplored, in particular, whether and to what extent a population of states of particle-phonon nature is present in isotopic chains reached via multiple-particle transfer mechanism. The Ar (neutron transfer channels) [21] and Cl [22] (one proton stripping channels) isotopes have been populated in the ^{40}Ar+^{208}Pb reaction. Their γ spectra display strong transitions which can be connected with the single-particle or single-hole states. In addition, through the whole isotopic chain also states that involve combinations of a single particle or hole with a collective boson have been populated. For example, in ^{40}Ar one notices a very strong population of the 2^+ state. In ^{41}Ar, the one-neutron transfer channel, besides the low lying states with a pronounced single-particle character, as the $3/2^-$ state, the decay of the $11/2^-$ state has been observed. A similar pattern occurs in other populated odd Ar isotopes (see Fig. 3 top panel). These $11/2^-$ states can be understood as a coupling of a collective boson to single-particle states (i.e. $|2^+, (f_{7/2})^1\ >)$ giving a $11/2^-$ stretched configuration. The properties of such states are closely connected with the properties of the vibration quanta, allowing one to follow the development of collectivity in odd isotopic chain, a phenomenon widely discussed in even-even isotopes (see Fig. 3 top panel). The significant population of states that match a stretched configuration of the valence neutron coupled to the vibration quanta, demonstrates the importance of the excitation of the states whose structure can be explained with the same degrees of freedom which are needed in the reaction model: surface vibrations, and single particles. It is through the excitation of these modes that energy and angular momentum are transferred from the relative motion to these intrinsic degrees of freedom and that mass and charge are exchanged among the two partners of the collision.

In recent years, a special interest was dedicated to the breakdown of the N = 28 magic number, or vanishing of the proton Z = 16 sub-shell gap [24, 25]. The behavior of the proton $s_{1/2}$ and $d_{3/2}$ orbitals was crucial in understanding these effects. In chlorine nuclei one expects that the $s_{1/2}$ orbital is completely filled and that the unpaired proton occupies the $d_{3/2}$ orbital. Figure 1 shows the γ spectra of the ^{39}Cl isotope, where the strongest line belongs to the decay of the $1/2^+$ state to the ground $3/2^+$ state, with a dominant single particle configurations. With increasing neutron number, the $d_{3/2} - s_{1/2}$ splitting is reduced and mixing between different proton configurations increases. This mixing results in nearly quasi-particle states where the heavy Cl isotopes can be viewed as one proton coupled to the corresponding quadrupole excitation of $^{(A-1)}$S isotope. This behavior in Cl isotopes can be demonstrated by inspecting the $5/2^+_1$ states (see Fig. 3 bottom panel) [22]. A similar trend of the energies of the higher spin states, $7/2^+$ and $9/2^+$, has been observed.

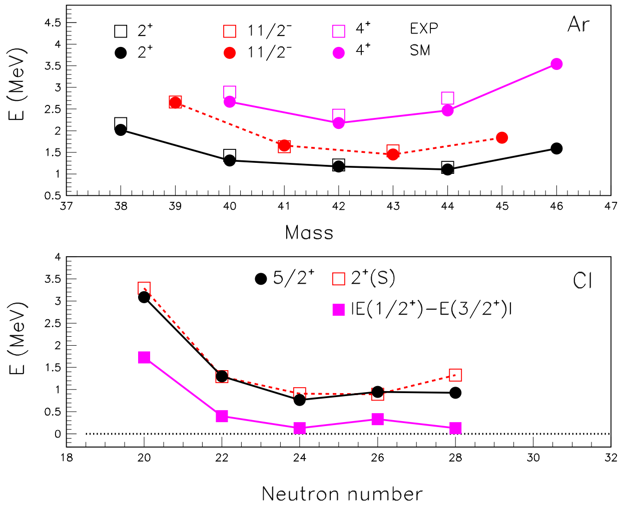

Figure 3. (Top): Energies of the 2^+, 4^+ and $11/2^-$ states of argon isotopes with N = 20-28. Solid circles are shell-model calculated energies, whereas open squares are the energies of the adopted level in ^{39}Ar, recently measured $11/2^-$ in ^{41}Ar [21] and ^{43}Ar [23]. In the most recent compilation of the ^{45}Ar level properties, a level at 1911(5) keV is a good candidate for the $11/2^-$ state, and was added for completeness. (Bottom): Absolute energy difference between the lowest $1/2^+$ and $3/2^+$ states in the odd-even chlorine isotopes (filled squares, violet) and excitation energies of the $5/2^+$ states (filled circles, black), compared with the energies of the 2^+ states in S isotopes (empty squares, red), as a function of the neutron number. Curves are here only to guide eyes.

A strong excitation of states whose dominant structure can be viewed as a particle or hole coupled to the quadrupole or octupole excitation has been also observed in many other isotopic chain populated by multi-nucleon transfer reactions [9, 26–28].

4.2 Pair correlations

As already discussed, in Sec. 3, in order to obtain a good description of the experimental total cross sections for the different isotopes populated in the reaction one has to include, in the theoretical model, the degrees of freedom related to the transfer of pairs of nucleons, both protons and neutrons. The influence of these degrees of freedom was particularly visible in the total cross sections of the proton transfer channels. Contrary to the neutron pick-up channels where the effect of the transfer of correlated neutron pairs was imbedded in the much larger cross sections. Thus, to have evidence of the excitation of these modes in the neutron sector the analysis of the total kinetic energy distributions have been performed. Figure 4 displays the TKEL distributions for the Ca isotopes (the quasi-elastic, $(+1n)$ and $(+2n)$ transfer channels) populated in the different measurements: the ^{40}Ca+^{208}Pb reaction measured by a time-of-flight spectrometer (middle) [18], the ^{40}Ca+^{96}Zr reaction where the Ca-like fragments have been detected

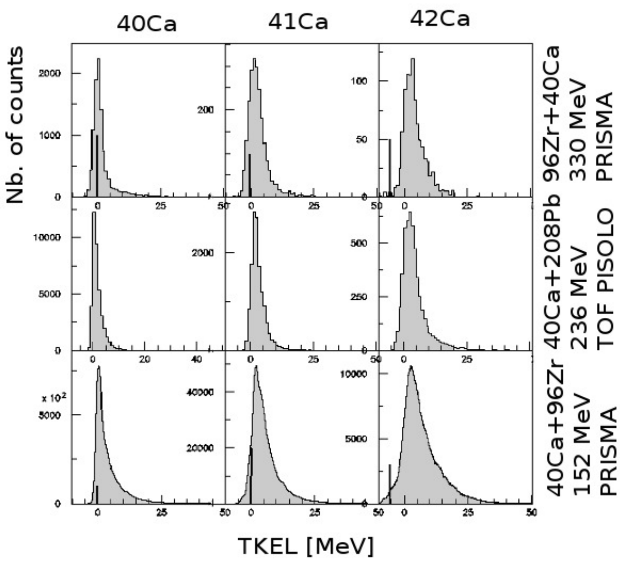

Figure 4. TKEL of ^{40}Ca (left), ^{41}Ca (middle) and ^{42}Ca (right) populated in the ^{96}Zr+^{40}Ca reaction measured in the inverse kinematic by the PRISMA spectrometer (top), and in the ^{40}Ca+^{208}Pb reaction measured by the time-of-flight spectrometer PISOLO (middle) and in the ^{40}Ca+^{96}Zr measured by the PRISMA spectrometer (bottom). Horizontal lines indicate the ground to ground state Q-value.

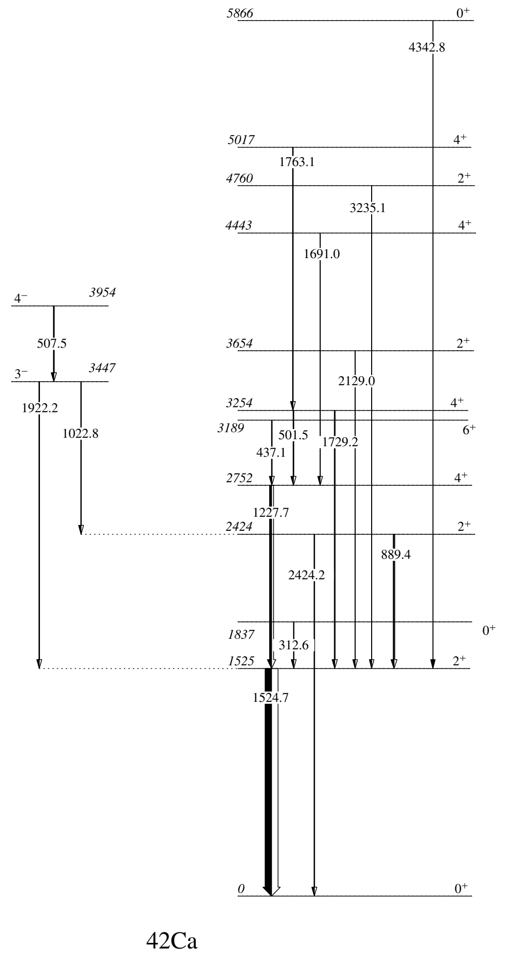

Figure 5. Level scheme of ^{42}Ca, populated via (+2n) channel in ^{40}Ca+^{96}Zr. Relative γ-ray intensities are indicated by the width of the arrows.

in the PRISMA spectrometer in the direct (bottom) and inverse kinematic (top). As can be appreciated from Fig. 4 the TKEL spectra display a well defined maximum, which is in the case of the ^{42}Ca, the (+2n) channel, shifted to high energy losses, leaving the ground states unpopulated (notice that the optimum Q-value for all neutron transfer channels is close to 0). The centroid of the TKEL spectra of the (+2n) channel is consistent with the population of a 0^+ state at ~5.8 MeV where a pairing-vibration state should be located [29]. In fact, systematic studies of (p, t) and (t, p) reactions [30, 31] identified the calcium region as the only known region where the cross sections for the population of the excited 0^+ states is larger than the ground state. This behaviour is essentially due to the role played by the single particle states $f_{7/2}$ and $p_{3/2}$. While the first dominates the ground state wave function of ^{42}Ca the second dominates the wave function of the 0^+ state at ~5.8 MeV. The coupling of the PRISMA spectrometer to the CLARA γ array allows the observation of the decay pattern of the populated states (see Fig. 5). The observed γ-transition at 4340 keV is consistent with a decay from the 0^+ at 5.8 MeV to the 2^+_1 state. The limited statistics accumulated for this transition (we remark that such high energy γ rays have a low photo-peak efficiency) does not allow to deduce the spin of the populated level, though the distribution over the rings of CLARA shows an isotropic pattern but with very large error-bars.

In this context, it is also important to investigate the role played by neutron-proton correlations. Nuclear models point out that such a correlation is expected to be strongest in $N \sim Z$ nuclei, where protons and neutrons occupy the same orbitals [32]. As known, multinucleon transfer reactions allow the transfer of large number of nucleons, and the strength of each of these channels is governed by form factors and optimum Q-value consideration. In order to study proton-neutron correlation one has to use systems where the population of the (np) channels is allowed by the Q-value.

This situation is met in the ^{40}Ar+^{208}Pb system, where the population of the (+np) channel is allowed by the Q-value consideration, The total cross sections in ^{40}Ar+^{208}Pb have been compared with the semi-classical code GRAZING. The preliminary results show that while the GRAZING code describes well the cross sections in the (+1p) and (+1n) channels, it strongly underestimates the measured cross sections in the (+np) channels (note that the GRAZING code includes only the independent proton and neutron transfers). In addition, the study of the coincident

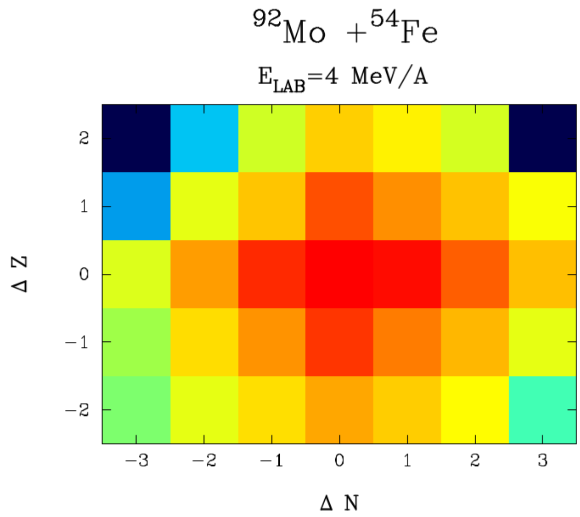

Figure 6. Total cross section in the ΔN (number of transferred neutrons) vs. ΔZ (number of transferred protons) matrix calculated with the code GRAZING for the ^{92}Mo+^{54}Fe reaction at an energy close to the Coulomb barrier. Positive and negative numbers correspond to pick-up and stripping channels, respectively.

γ spectrum of ^{42}K, shows that beside the population of the low-laying negative parity states, whose structure can be viewed as a multiplet arising from the coupling of the unpaired proton in the $d_{3/2}$ and the unpaired neutron in the $f_{7/2}$ orbitals, the population of the higher lying positive parity states has been observed. Those states can be explained as the excitation of the proton to the $f_{7/2}$ orbital and its coupling to the unpaired neutron in the same orbital.

The other approach in the study of the role played by neutron-proton correlations is the study of the excitation functions at energies below the barrier, where the interacting nuclei are only slightly influenced by the nuclear potential and Q values are restricted to few MeV for the open transfer channels. These conditions diminish the complexity of coupled channel calculations and quantitative information may be more reliable extracted on the nucleon-nucleon correlations. Such experimental techniques has been recently employed in the study of the neutron-neutron correlations [19, 33]. In this sense we recently studied the ^{92}Mo+^{54}Fe system by exploiting the large acceptance of the spectrometer PRISMA and by employing inverse kinematics. This system cope well with the peculiar experimental constraints of the inverse kinematic measurement at sub-barrier energies, and a significant transfer yield could be detected at the level of 10^{-4} with respect to the elastic channel. In addition, with the ^{92}Mo+^{54}Fe reaction we are coming as close as heavy-ion induced transfer reactions allow to the $N = Z = 27$ region i(see Fig. 6) which is presently at the focus in the light-ion induced reactions. Therefore, the possibility to compare enhancement factors in light-ion and heavy-ion induced reactions in that region will strongly help in the understanding of pair transfer degrees of freedom.

5 Summary

The advent of the last generation large solid angle magnetic spectrometers, coupled to large γ arrays, ensured significant advances in the field of multinucleon transfer reactions at energies close to the Coulomb barrier. Through multiple transfers of neutrons and protons one can populate nuclei moderately far from stability, especially in the neutron-rich region. From the point of view of the mechanism, present focus is also on the study of the production and properties of the heavy binary partner [34]. Of special interest is to get access to neutron rich heavy nuclei, important also for astrophysics. Even with the presence of secondary effects, namely nucleon evaporation and transfer induced fission, which lower the final yield, multinucleon transfer reactions still provide a sufficient cross sections especially in the regions where other production methods, like fission of fragmentation, have severe limitations or cannot be used at all. These studies will be of increasing relevance for the ongoing and foreseen experiments with radioactive beams [35, 36].

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References

[1] L. Corradi, G. Pollarolo, and S. Szilner, J. of Phys. G **36**, 113101 (2009).
[2] S. Szilner *et al.*, Phys. Rev. C **76**, 024604 (2007).
[3] D. Montanari *et al.*, Eur. Phys. J. A **47**, 4 (2011).
[4] H. Savajols *et al.*, Nucl. Phys. A **654**, 1027c (1999).
[5] A. Cunsolo *et al.*, Nucl. Instrum. Methods A **481**, 48 (2002).
[6] A. Gadea *et al.*, Eur. Phys. J. A **20**, 193 (2004).
[7] A. Gadea *et al.*, Nucl. Instrum. Methods A **654**, 88 (2011).
[8] S. L. Shepherd *et al.*, Nucl. Instrum. Methods A **434** (1999) 373.
[9] S. Lunardi *et al.*, Phys. Rev. C **76**, 034303 (2007).
[10] J. J. Valiente-Dobón *et al.*, Phys. Rev. Lett. **102**, 242502 (2009).
[11] A. Winther, Nucl. Phys. A **572**, 191 (1994); Nucl. Phys. A **594**, 203 (1995); program GRAZING, htpp:/www.to.infn.it/~nanni/grazing.
[12] V. Zagrebaev and W. Greiner, Phys. Rev. Lett. **101**, 122701 (2008).
[13] C. Simenel, Phys. Rev. Lett. **105**, 192701 (2010).
[14] G. Scamps and D. Lacroix, Phys. Rev. C **87**, 014605 (2013).

[15] K. Sezikawa and K. Yabana, Phys. Rev. C **88**, 014614 (2013).
[16] L. Corradi *et al.*, Phys. Rev. C **66**, 024606 (2002).
[17] S. Szilner *et al.*, Eur. Phys. J. A **21**, 87 (2004).
[18] S. Szilner *et al.*, Phys. Rev. C **71**, 044610 (2005).
[19] L. Corradi *et al.*, Phys. Rev. C **84**, 034603 (2011).
[20] T. Mijatović *et al.*, Nuclear Structure and Dynamics 2012, AIP Conf. Proc. **1491**, 346 (2012).
[21] S. Szilner *et al.*, Phys. Rev. C **84**, 014325 (2011).
[22] S. Szilner *et al.*, Phys. Rev. C **87**, 054322 (2013).
[23] D. Mengoni *et al.*, Phys. Rev. C **82**, 024308 (2010).
[24] O. Sorlin and M.-G. Porquet, Prog. Part. Nucl. Phys. **61**, 602 (2008).
[25] E. Caurier, G. Matrinez-Pinedo, F. Nowacki, A. Poves, and A. P. Zuker, Rev. Mod. Phys. **77**, 427 (2005).
[26] D. Montanari *et al.*, Phys. Lett. B **697**, 288 (2011).
[27] F. Recchia *et al.*, Phys. Rev. C **85**, 064305 (2012).
[28] S. Bhattacharyya *et al.*, Phys. Rev. C **79**, 014313 (2009).
[29] R. A. Broglia and A. Winther, *Heavy Ion Reactions* (Addison-Wesley Pub. Co., Redwood City CA, 1991).
[30] R. A. Broglia, O. Hansen and C. Riedel, *Advances in Nuclear Physics* Vol. **6** (Plenum, New York, 1973).
[31] M. Igarashi, K. Kubo and K. Tagi, Phys. Rep. **199**, 1 (1991).
[32] P. Van Isaker, D. D. Warner and A. Frank, Phys. Rev. Lett. **94**, 162502 (2005).
[33] D. Montanari *et al.*, Phys. Rev. Lett. **113**, 052501 (2014).
[34] L. Corradi *et al.*, contribution to this conference.
[35] http://www.ganil.fr/research/developments/spiral2 *The Scientific Objectives of the Spiral2 Project (2006)*
[36] *SPES:* (http://web.infn.it/spes/) *Exotic beams for science*