Reactions with exotic nuclei: recent results and challenges

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Abstract. The interaction of exotic nuclei with various targets and implying different types of reactions allows to access a rich variety of information. Some examples of the latest results and recent developments related to some of these reactions are reviewed.

1. Introduction
With the availability of secondary beams of relatively good optical qualities and intensities, and thanks to the construction of sophisticated experimental equipment, it is now possible to perform experiments where the secondary beams interact with a target, and to study the different reactions, which come into play. Reactions with exotic beams are mainly used to study the structure of exotic nuclei. This is specifically the case of the so-called direct reactions, namely elastic and inelastic scattering, transfer and knock-out reactions. This is presently the main focus of experiments related to reactions with exotic nuclei, and the present review will illustrate some of the many subjects that can be addressed in this domain.

Direct reactions with exotic beams are usually performed in inverse kinematics, by using light targets with simple structure such as proton, deuterons, or alpha. The structure information on the nucleus of interest are extracted either via the missing mass method from the kinematical characteristics (angle and energy) of the light recoil nucleus, or via the invariant mass method where the fragments from the ejectile are measured in order to reconstruct their relative energy spectrum.

We shall review in the following the different types of direct reactions and the latest results obtained especially for the light neutron rich nuclei. Reactions mechanisms with exotic beams and their specificities are also a subject, which will be briefly addressed.

2. Elastic scattering
Elastic scattering with stable nuclei provided most of the available information on the nuclear interaction potential, especially in the case of light projectiles, where both phenomenological and microscopic optical potential models have been developed to describe experimental results. With the secondary beams, these studies have gained renewed interest, since it became possible to measure elastic scattering for nuclei lying far from stability, to obtain the interaction potentials needed to analyze inelastic scattering or transfer reaction cross sections. The latest results are related to the spin-orbit part of the nuclear interaction potential.

2.1. Determination of spin observables from elastic scattering on a polarized proton target
The spin-orbit interaction is related to surface properties. This is why there are strong presumptions
that the spin-orbit interaction and hence magic numbers may change very significantly far from
stability. In order to investigate this question a polarized target was developed at CNS Tokyo [1] and
used in the first experiment measuring elastic scattering of $^6$He and $^4$He secondary beams, in inverse
kinematics.

The polarized target uses photo-excited aromatic molecules and is used under modest conditions:
low magnetic field (<0.1 T) and relatively high temperature (77K). The low magnetic field allows
the detection of the low energy recoil protons from the target without strong deviation of their trajectory.

The protons in the target made of crystals of naphthalene ($C_{10}H_8$) are polarized by transferring
electron polarization in photo-excited triplet states of pentacene molecules ($C_{22}H_{14}$) via cross
polarization. The experiments were performed at RIKEN. The experiment with $^4$He is still under
analysis. Here we report on the results obtained with $^6$He at 71 MeV/nucleon [2]. The angular
distributions of differential cross section and vector analyzing power $A_y$ are shown in Figure 1. Only
statistical error bars are shown in the figure. The systematic uncertainty in $A_y$ reaches 19% and is
mainly determined by the uncertainty in absolute normalization of proton polarization. The solid lines
correspond to the result of a full six-body $g$-matrix folding calculation [3], including the non-locality
of the p-A interaction due to an exchange term in a fully microscopic way. Nuclear structure effects
are taken into account through single particle wave function obtained with a Woods-Saxon potential
with a halo component. Whereas the differential cross section is very well reproduced by the
calculation, the predicted angular distribution of the vector analyzing power deviates from the data for
angles above 60°. In order to reproduce the data on the whole angular range, the depth of the spin-orbit
potential has to be reduced, from around 5 MeV for light stable nuclei such as $^4$He, $^{12}$C or $^{16}$O down to
1.3 MeV. The calculations performed in the framework of the cluster-folding model [2] seem to
indicate that the sensitivity of $A_y$ does not originate directly from the direct valence neutron
contribution, but from the recoil motion of the alpha-core in $^6$He, which produces a smearing of the
core distribution, and therefore a reduction of the spin-orbit potential.

![Figure 1. Cross section and vector analyzing power for the p-$^6$He elastic scattering at 71 MeV/nucleon (filled circles) together with data from ref [4]. Results from 6-body folding calculation [3] with Woods-Saxon single particle wave functions including halo, are shown by the solid line.](image)

The next generation of experiments with the polarized proton target will correspond to the study of
($\bar{p}, 2p$), ($\bar{p}, pn$), ($\bar{p}, n$) in order to determine the spin and parity of the different states which will be
populated in these reactions.
2.2. Determination of density distributions from elastic scattering

When approaching the drip-lines, the binding energy of the last nucleons approaches zero, and this causes long tails of the wave function at least for low angular momentum. Low density regions of nuclear matter result, where special correlations may occur. Appropriate measurements, such as elastic scattering on both hadronic and electromagnetic probes, may explore matter and charge density distributions especially for halo nuclei, with the final goal to reach the proton and neutron density distributions.

2.2.1. Matter density distributions. Probing the nuclear matter distributions in stable nuclei with proton elastic scattering at energies close to 1 GeV is a well established method. It was extended more recently to the case of light neutron rich nuclei in order to study the extension of the neutron halo [5-8]. Several experiments were performed at GSI for that purpose, using the IKAR active target filled with hydrogen which was used both as target nucleus and detection gas. The differential cross sections \( \frac{d\sigma}{dt} \) were measured at low momentum transfer and analyzed within a Glauber multiple scattering model, using phenomenological density distributions, with parameters obtained from the fit to the experimental data. The results obtained for the matter radii of \(^6\)He, \(^8\)Li are summarized in Table 1. The latest results correspond to \(^{12}\)Be and will be published soon.

Table 1. Values of the matter radii, core radius and halo radius deduced from proton elastic scattering

| Nucleus | \( R_{\text{matter}} \) (fm) | \( R_{\text{core}} \) (fm) | \( R_{\text{halo}} \) (fm) | \( R_{\text{matter}} \) (fm) | \( R_{\text{core}} \) (fm) | \( R_{\text{halo}} \) (fm) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(^4\)He | 1.49(3) | 1.88(12) | 3.31(28) | 2.44(6) | 3.71(20) | 6.85(58) |
| \(^6\)He | 2.45(10) | 1.55(15) | 3.22(4) | 2.53(3) | 6.85(58) |

2.2.2. Charge density distributions. The determination of the charge density distribution is obtained from the measurement of angular distribution of electron scattering cross sections. There are some examples of electron scattering experiments for unstable nuclei having long lifetimes such as \(^3\)H or \(^{14}\)C [9,10]. However, electron scattering experiments for short lived nuclei require the development of new techniques. The ELISE project at FAIR will use a collider between an electron storage ring and a large ion storage ring with large acceptance and cooling devices in order to achieve the necessary luminosity. ELISE has been postponed to the second phase of FAIR, and will not be operational in the next few years. Electron scattering with exotic nuclei is also the aim of the SCRIT project (Self Confining Radioactive Isotope Target) [11], presently under construction and commissioning at RIKEN. The whole system is formed of an electron accelerator, an electron storage ring where SCRIT is installed, an ISOL radioactive ion beam generator, and a detector system. The electron accelerator will be used to provide the electron beam at the entrance of the storage ring and also to produce the radioactive species by photofission on a UCx target. A prototype of SCRIT has been tested with stable Cs ions at the Kaken Storage Ring (KSR) in Kyoto [12]. Apart from the electron beam which ensures the transverse confinement of the ions, SCRIT itself consists of an ion source, a deflector, a system of electrodes which form a mirror potential to localize longitudinally the trapped ions, an analyzer for monitoring the ions extracted from the trap according to their mass to charge ratio, and electron detectors (see Figure 2). The tests performed at KSR achieved a luminosity of \( 10^{26} \) cm\(^{-2}\)s\(^{-1}\), with only around \( 10^6 \) trapped ions located on the electron beam, and a trapping time limited to 50 ms, in order to mimic electron scattering on short lived nuclei. The angular distribution measured during this test could be perfectly reproduced by a distorted wave calculation. However, an increase in luminosity by one (resp. two) order of magnitude will be necessary in order to reach the second (resp. third) minimum of the momentum distribution and to have a precise determination of the charge density distribution. This increase will be obtained by an increase of the beam intensity and by a reduction of the ion beam emittance at the exit of the ion source.
3. Inelastic Scattering

Inelastic scattering is extensively used to measure low lying collective states in exotic nuclei via Coulomb excitation. This subject was addressed in this conference by Alexandra Gade [13].

Giant resonances are collective excitations of nuclei, located at relatively high excitation energy, and involving a large fraction of their nucleons. Their study has brought a lot of information on collective and single particle properties of stable nuclei [14]. Experimentally, the study of giant resonances in exotic nuclei has been mainly limited to the isovector dipole resonance in neutron-rich oxygen [15], neon [16] and tin [17] isotopes. They provided the first evidence of soft modes in exotic nuclei. The isoscalar Giant Monopole Resonance (GMR) is a compression mode allowing to obtain a measurement of the nuclear matter incompressibility, which is itself a parameter of major importance for the nuclear equation of state and for calculations describing neutron stars or supernovae. Several questions remain open concerning this parameter. Indeed for the same nucleus, the relativistic approaches always provide a higher value for nuclear matter incompressibility than non-relativistic approaches. Furthermore, for the same model, $^{208}$Pb is stiffer than other nuclei such as Sn, Zr or Sm. The origin of these differences is not fully understood, but it has been shown that the neutron-proton asymmetry dependence of the incompressibility $K_{\text{sym}}$ plays also a role as well as the density dependence of the functional. Therefore the usual method to determine the nuclear matter incompressibility, which is to measure precisely the GMR on some few (in general magic) stable nuclei, is probably not relevant. Instead the GMR should be measured on isotopic chains, in order to probe different densities, different pairing and different asymmetries [18].

The first experiment to measure the GMR in an exotic nucleus was performed at GANIL with a $^{56}$Ni secondary beam at 50 MeV/nucleon and the MAYA active target filled with deuterium gas [19]. The properties of the GMR could be deduced from the excitation energy spectrum and the angular distributions with results comparable to neighboring stable nuclei such as $^{56}$Fe or $^{58}$Ni [20]. The next step will be to measure $^{68}$Ni, in order to span a larger range of asymmetry. The long Sn isotopic chain would be also worth investigating. The limited number of results available today is due to the intrinsic
difficulty of the experiments. Indeed, the properties of the GMR are deduced, via the missing mass method, from the kinematic characteristics of the light recoil nucleus from the target. As the GMR cross section is strongly peaked at 0°, it requires the detection of very low energy particles. In the case of $^{56}$Ni(d,d') experiment at 50 MeV/nucleon, the energy range of interest for the recoil deuteron was between 500 keV and 2.5 MeV. Furthermore, a relatively broad angular range in the laboratory frame had to be covered, requiring a large angular coverage, low energy threshold and a thin target to minimize energy and angular straggling. The active target detector concept allows to combine a large target thickness, which is necessary for experiment with low intensity secondary beams, and the requirements mentioned above, by the possibility to obtain a 3-dimensional tracking reconstruction of the trajectories, and therefore a reconstruction of the reaction vertex, which allows to determine the reaction energy.

4. Transfer and Knockout reactions

Transfer and knock-out reactions are complementary reactions (in terms of beam energy) which preferentially populate single particle states. Very detailed structure information can be obtained for the most exotic nuclei, even beyond drip lines: level schemes from the energy spectra, momentum transfer (even the spin and parity in some cases) from the angular or momentum distributions, and the single particle structure from the spectroscopic factors. Many new results were obtained in the last few years: for the light neutron rich isotopes of He and/or Li, the latest results were obtained at GSI by knock out reactions of $^8$He, $^{11}$Li and $^{14}$Be beams on a proton target [21,22,23] and at GANIL by transfer reactions induced by the ISOL $^8$He beam produced with SPIRAL [24,25].

We shall focus here on $^9$He, a system for which the experimental situation is still not completely clear. The first experiments, where $^9$He was produced by ($\pi^+,$$\pi^-$), (13C,13O), (14C,14O) double charge exchange, reported a ground state at 1.3 MeV above the $^8$He+n threshold [26,27]. However, an s-state around 0.2 MeV above $^8$He+n threshold was reported in a two-proton knock-out reaction from $^{11}$Be on Be target, with an upper limit for the scattering length of $a_s$<-10fm [28]. More recent results from the same reaction resulted in a value for $a_s$ rather in the range between -2 and 0 fm [29]. The latest results from knock out reaction have been obtained at GSI with a 280 MeV/nucleon $^{11}$Li beam impinging on a liquid hydrogen target [23]. The corresponding relative energy spectrum is reported on Figure 3.

Three different approaches were used to describe the low energy part of the spectrum: effective range approximation, R-matrix and S-matrix theories. The best fit obtained within the effective range approximation is shown by the solid line on Figure 4 and corresponds to the sum of s-wave component with a scattering length of about -3 fm, and 2 resonances at 1.33 and 2.42 MeV. The parameters obtained using the effective range approximation for the low energy spectrum were recalculated to the R-matrix and S-matrix formalisms. The deduced R-matrix parameters are interpreted as a very broad resonance located several MeV above the $^8$He+n threshold. The S-matrix pole is found at real negative energy, signaling the appearance of a virtual state. It is therefore concluded that neither the R-matrix parameters nor the S-matrix pole position can be identified with the $^9$He ground state with $J^π=1/2^+$, and that the intruder s-state for the N=7 isotones, well established for $^{11}$Be and $^{10}$Li, seems to disappear for $^9$He [23]. The low energy structure observed in the relative energy spectrum is considered as a kind of threshold phenomenon.

On the low energy side, three transfer experiments were dedicated to the study of $^9$He via $^8$He(d,p) reaction. The reaction was studied at Dubna at 25 MeV/nucleon with a cryogenic deuterium target [30]. The data shown on Figure 4, present two broad structures at 2 and 4.2 MeV in $^9$He. The angular correlation pattern measured in this experiment was explained by the interference of a ½- resonance at 2 MeV with a virtual ½+ state (a limit $a_s$>-20 fm was obtained for the scattering length), and with a 5/2+ resonance above 4.2 MeV.
Figure 3. Relative energy spectrum of $^8$He+n obtained with a 280 MeV/nucleon $^{11}$Li beam on a cryogenic hydrogen target. The dashed line is the result of a fit assuming an s-wave scattering. The dotted and dashed-dotted curves correspond to Breit-Wigner shaped resonances. The solid line is the sum of the three components (from [23]).

Figure 4. Missing mass spectrum for $^9$He by transfer reaction on a cryogenic deuterium target. The black circles with error bars correspond to the data of [30]. The solid lines correspond to theoretical calculations within a single-particle potential: yellow, green and red lines show respectively the contributions of $\frac{1}{2}^+, \frac{3}{2}^-$ and $5/2^+$ states. The black line corresponds to the total result.

The same reaction was studied at GANIL in two successive experiments, both at 15 MeV/nucleon and using polypropylene foils as targets. The missing mass spectrum obtained for $^9$He in the first experiment [31] (Figure 5) was deduced from the energy-angle correlation of the proton emitted at backward angle and detected with the MUST array [32]. Despite relatively poor statistics, several peaks can be distinguished at 1.34, 2.38, 4.3, 5.8 MeV. Proton angular distributions were compared with DWBA predictions for neutron transfer to unbound single-particle states in order to determine the transferred angular momentum and spectroscopic factor. The small natural widths (well below single particle expectations) of $^9$He states previously observed in double charge-exchange reactions are
unexpected and in contrast to broad resonances in neighbouring unbound nuclei. These data confirm the existence of the two narrow low-energy resonant states (E=1.34 and 2.38 MeV) of [26, 27], but are difficult to reconcile with the broad resonances observed in [30]. The measured l = 1 spectroscopic factor for the 1.34 MeV resonance is much smaller than 1, indicating a strong fragmentation of the p1/2 single particle state. As for the s1/2 neutron shell, the present (d,p) experiment also shows that the 9He ground state is located just above neutron threshold (E=0.1 MeV) with a J=1/2+, in agreement with the results of [28]. A more recent experiment, performed within the MUST2 detector array in order to get a higher statistics, is presently under analysis. The preliminary spectrum is presented on Figure 6 and seems to confirm the previous MUST results, at least for the low energy part of the spectrum [25]. The apparent discrepancy (above 2 MeV) between the spectra presented on Figure 5 and 6 is mainly attributed to the difference in statistics between the two experiments, of the order of a factor 10.

The example of 9He is particularly illustrative of the efforts, which are performed presently to reach a better understanding of the structure of the most exotic nuclei. Many other cases have also been addressed in recent experiments, such as 12,13Li [21,33,34]. The question of mirror symmetry of shell quenching phenomena was also addressed with the 14O(p,t)12O reaction, in order to compare the shell structure of 12O and 13Be [35]. Heavier nuclei are also investigated especially in the regions where shell structure modifications are observed. There exists already a dense literature for nuclei around N=16,20 [36,37]. First results start to appear around N=28 and N=50 [36,38-40].

Figure 5. Missing mass spectrum obtained for 3He by transfer reaction at GANIL/SPIRAL. The histogram corresponds to the data obtained with the MUST array. The dotted line corresponds to the background due to phase space. Figure from [31].

5. Sub-barrier fusion reactions
Impressive progress has been done on the subject of sub-barrier fusion reactions induced by weakly bound nuclei, both on the sensitivity of the measurement and on the understanding of the low energy reaction mechanisms [41, 42]. In order to be able to measure low cross sections below Coulomb barrier with low intensity beams (typically 10^4pps), new methods had to be developed in order to increase the sensitivity and to be able to extract a weak signal in the presence of the high background due to beta decay: an activation technique was developed, involving simultaneous measurement of X
and γ rays emitted in electron capture decay of the evaporation residues [43]. The method was applied to the He isotopic chain, where the nucleon emission threshold varies from 20.5 MeV to 0.9 MeV, provides unique opportunities for studying the effect of the intrinsic structure on the fusion reaction and tunneling process. The fusion residues, after neutron evaporation, of the compound nuclei are characterized off-beam by their radioactive decays with X-γ coincidences. The measured fusion cross section for He isotopes with $^{197}$Au are plotted on Figure 7 as function of center of mass energy [44-46] and compared to predictions from one dimensional barrier penetration calculation for $^4$He+$^{197}$Au obtained with the nuclear potential parametrization of [47].

![Figure 6. same as figure 5, for the data obtained with MUST2. The energy-dependent Breit-Wigner resonances together with the underlying background have been obtained from a fit of the data (preliminary analysis).](image)

The good agreement observed for $^4$He confirms the point like behavior in this case. At energies below the barrier, both $^6$He and $^8$He have larger fusion cross sections than $^4$He as expected, but are surprisingly very similar. Thus, it seems that it is easier for a loosely bound and essentially isotropic system like $^8$He to transfer part of the neutron excess in a peripheral reaction than to readjust the outer skin of the system and tunnel as a whole [46].

6. Conclusions and perspectives

With the possibility to study reactions induced by secondary beams, a new class of experiments with exotic nuclei has become possible and opens new insight into the structure of these nuclei. Experimental sensitivity was greatly increased during the last decade, allowing to study direct reaction or fusion cross sections with radioactive beam intensities as low as $10^2$ to $10^5$ ions per second, many orders of magnitude below what was achieved with stable beams. This breakthrough was possible thanks to important development performed on experimental techniques. Many new pioneering pieces of equipment had to be developed and constructed: beam tracking detectors, able to handle high counting rates with the highest efficiency, new detectors array combining large angular coverage, high granularity, large energy range, low thresholds, and modularity allowing to adapt them to the reaction of interest. Different groups explored various solutions to reach these challenging goals: solid state detectors arrays for light charged particles [32, 48-50], active targets [51-53], solenoid spectrometer [54].
Figure 7.
Measured fusion cross section as a function of center of mass energy for the 3 systems $^{4,6,8}$He+Au. The dotted line corresponds to the one-dimensional barrier penetration calculation for $^4$He+$^{197}$Au obtained using the parametrization of [46] for the nuclear potential. The inset shows the binding energy of the 3 helium isotopes as a function of A.

The target development is another issue for which important efforts were dedicated in many laboratories. The development of cryogenic targets, polarized targets, self-confining target was mentioned in the present paper.

Finally, the availability of a larger variety of beams, with higher intensities is the goal of the new facilities recently opened, such as RIBF at RIKEN, or presently under project or construction, such as SPIRAL2 at GANIL, NUSTAR@FAIR, HIE-ISOLDE or FRIB at NSCL.

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