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# Study of pairing and clusterisation in light nuclei through nuclear break-up

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**Abstract.** Nuclear break-up is a powerful tool to investigate nuclear structure as it is sensitive to the quantum properties of the emitted particles. This reaction mechanism has been used to investigate several aspects of correlations. First, the case of $^{11}$Be was studied where the spectroscopic factors for the two configurations where extracted. Secondly, the spectroscopic factor for alpha clusterization in the ground state of $^{40}$Ca was measured. Finally the correlation between the two neutrons in the halo of $^{6}$He emitted through break-up reactions showed strong contribution for the di-neutron configuration.

## 1 Nuclear break-up

Nuclear break-up occurs at few tens of MeV per nucleon. Among all other inelastic processes leading to the emission of one nucleon, the nuclear break-up, also called Towing Mode is characterized by the emission of a nucleon from the target on the same side as the projectile with an intermediate velocity and a large angle with respect to the beam axis. Knock-out reactions lead to a nucleon emitted around 90 deg. while pick-up break-up reactions lead to forward emission. The mechanism is understood the following way: when the projectile passes by the target, the nucleon inside the target feels its nuclear potential and is towed to be emitted to the continuum. This picture is confirmed by a theoretical model solving the time dependent Schrödinger equation (TDSE) for the wave function of a nucleon inside the potential of target when the projectile potential passes by.

The nuclear break-up was brought out in the $^{40}$Ar+$^{58}$Ni @ 44 MeV/A reaction where the neutron or proton knock-out was measured [1]. In addition to the statistical decay, a contribution was highlighted in the forward region. The angular distribution extracted for each excited state populated in the daughter nucleus showed very good agreement with the TDSE calculations (see Fig. 1). Therefore nuclear break-up is sensitive to the initial wave function (quantum numbers) of the nucleon inside the target and can be used as a tool to probe nuclear structure. Several other examples of the use of nuclear break-up will be shown below such as configuration mixing, pairing correlation and clusterization into alpha particles.

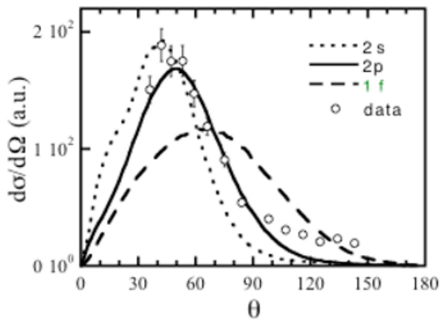


**Figure 1 :** Angular distribution of neutrons from the $^{40}Ar+^{58}Ni$ experiment compared to TDSE calculations for 3 different wave functions (this figure has been adapted from Ref.[1]).

## 2-Probing configuration mixing

The ground state of $^{11}Be$ is known to be a superimposition of two configurations that is to say (i) a $^{10}Be$ in its ground state and a neutron in the $2s_{1/2}$ and (ii) a $^{10}Be$ in its first deformed $2^+$ state with a neutron in the $1d_{5/2}$. The configuration mixing was estimated by breaking up the $^{11}Be$ and detecting the emitted neutron and the gamma rays emitted possibly in coincidence with the residual projectile. The energy distributions obtained compared to TDSE calculations enabled to extract a spectroscopic factor for the (i) configuration of $S_{2s}$ = 0,47± 0,04 and for the (ii) configuration of $S_{1d}$= 0,50 ± 0,20 [2].

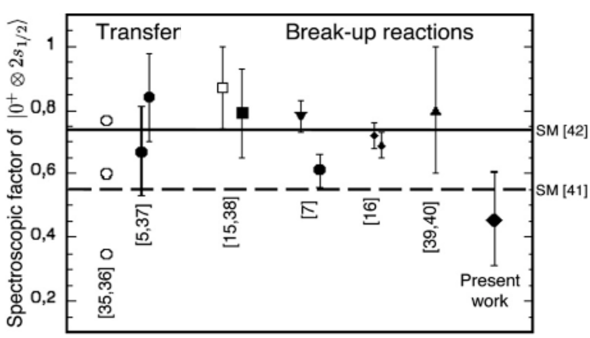


**Figure 2** : Comparaison of S(2s) measured in the present work (diamond) with previous results compiled in Ref.[2]. (the references quoted in this figures can be found in Ref.[2]).

A good agreement is obtained for the $S_{2s}$ spectroscopic factor with previous experiment (see Fig. 2) although the TDSE model does not take into account interferences between the two types of configurations.

## 3-Probing alpha clusterization in nuclei

Several nucleons can be towed in the nuclear break-up process; this can be also the case for light nuclear clusters such as alpha particles. In the case of symmetric matter, the formation of alpha clusters in the ground state of the N=Z nuclei is expected to increase the cross-section of alpha emission from the nuclear break-up.

The experiment was performed at GANIL with the reaction $^{40}Ca+^{40}Ca$ at 50 MeV/A (Ref.[3]). The projectile was identified with the SPEG spectrometer and the emitted alpha with the INDRA array. The missing mass spectrum of $^{36}Ar$ shows several excited states. For each of them the angular distribution of the emitted alphas can be extracted experimentally. Then, it can be compared to the TDSE calculation for the wave function of an alpha particle using an adjusted potential to reproduce $^{40}Ca$ rotational bands. This schematic calculation reproduces surprisingly well the width of the experimental curves as shown on Fig.3.

A spectroscopic factor of 1.2% was extracted for the alpha clusterization in the ground state of $^{40}Ca$. This is in agreement with shell model calculations [4] but not with the measurement of Umeda et al [5]. The clusterization at the surface of $^{40}Ca$ seems to be very small. This is in agreement with two types of recent calculations [6-7].

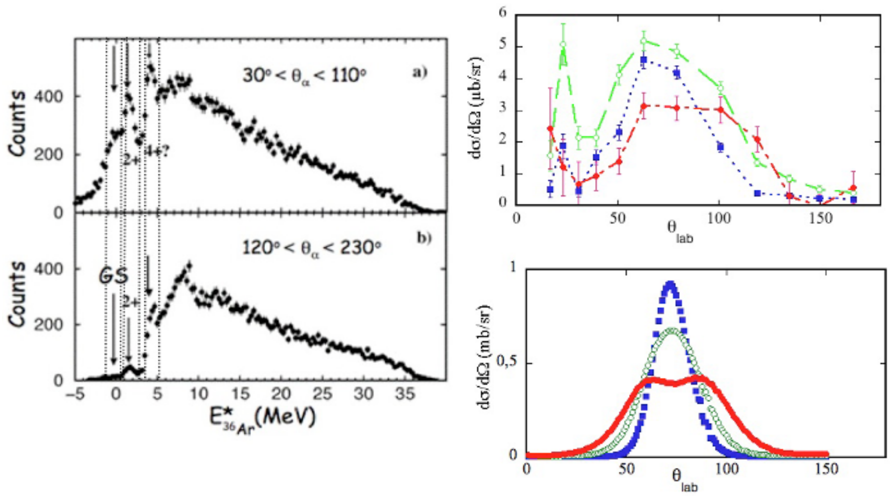


**Figure 3 :** (Left) Missing mass spectra for $^{36}Ar$ for an alpha particle detected forward (top) and backward (bottom). (Right top) Experimental angular distributions associated to each excited state in $^{36}Ar$. (Right bottom) Expected angular distribution from the TDSE calculations [3].

## 4- Probing pairing correlations in light nuclei

In the case of very light nuclei close to driplines, pairing plays an important role and particularly for borromean nuclei where the binding is insured by pairing. As nuclear break-up is sensitive to the wave function of the nucleons and also to spatial configuration, it can be a powerful tool to investigate pairing.

In the case of $^{6}He$, two configurations are expected from the three-body model: (i) a di-neutron configuration where the two neutrons lie close to each other and (ii) a cigar configuration where the neutrons are on opposite side with respect to the alpha core. In the first case (i) nuclear break-up should lead to the emission of the two neutrons together at large angle whereas in case (ii) one neutron will be towed and the second one be emitted in the direction of the beam as $^{5}He$ is not bound. The distribution of relative angle between the two emitted neutron should then give the information on the spatial correlation between the neutrons in the halo as illustrated by Fig. 4.

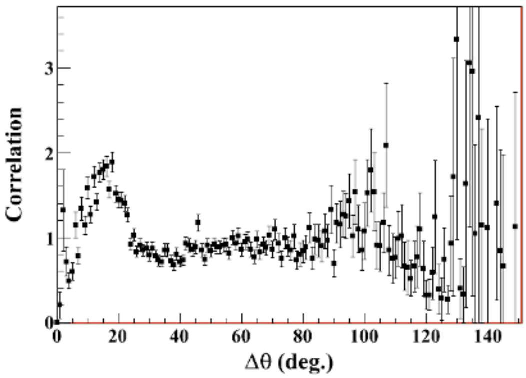


**Figure 2 :** Correlation function obtained from the experimental data. When it is close to 1, no correlation is seen and any deviation is a signature of correlation. A strong correlation is seen for small angles corresponding to di-neutron configuration.

The break-up of $^{6}$He on $^{208}$Pb was studied at GANIL using the Neutron Wall and the EDEN neutron detectors coupled to an annular Silicon stripped detector. Correlation functions were extracted experimentally (see Ref.[9] for more details). In order to compare the experimental results a new theoretical model has been developed. This reaction model TDDM$^{P}$ (Time Dependent Density Matrix) is a beyond mean-field model including pairing correlations [8]. It confirms that nuclear break-up is sensitive to the different configurations in $^{6}$He and seems to show that most part of the experimental distribution is reproduced by the di-neutron configuration.

## 5- Conclusion

Several studies with nuclear break-up show that it is a powerful tool to investigate nuclear clusterization from pairing to alpha clusters. Spectroscopic information or spatial correlations can be studied through this mechanism. In the future, efforts will be devoted to the study of cluterization into the B chain where AMD (Antisymmetrized Molecular Dynamics) calculations predict strong clusterization (Ref.[10]).

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