Probing the halo and cluster structure of exotic nuclei *

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Abstract: The Halo and cluster structure at the ground state of unstable nuclei are among the most exciting phenomena of current nuclear physics. Probing these structures requires a careful selection of reaction tools. In the past twenty years, knockout reactions have been used intensively to investigate spectroscopically the structure of unstable nuclei. In this report we have illustrated the latest development of the knockout reaction tool and have emphasized the recoiled proton tagging method. A quantitative criteria is developed to evaluate the quasi-free feature of the knockout process. The newly discovered "towing mode" reaction tool is also outlined and its applicability at transit energies is discussed.

Key words: halo nucleus, knockout reaction, proton tagging, towing mode

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1 Introduction

A nucleus used to be regarded as a deeply bound and compact quantum system. But since the advent of the radioactive nucleus beam, many new phenomena have been observed which introduce important changes to the traditional picture of nuclei. One aspect is the systematic evolution of the well known shell (single-particle) structure in the area away from the β-stability line, evidenced by the change of magic numbers [1]. Another aspect is the emergence of new degrees of freedom, such as the halo and cluster configuration at ground states for nuclei close to the dripline [2, 3]. The latter aspect is the most exotic feature of unstable nuclei and therefore the focus of this report.

So far a halo structure is identified for ^{6}He, ^{11}Li, ^{11}Be, ^{14}Be, ^{19}C at the neutron rich side and for ^{8}B at the proton rich side [4]. In addition, evidence of a halo structure was reported for ^{15}C, ^{17}B, ^{19}B, ^{22}N, ^{23}N, ^{23}O, ^{24}O, ^{24}F and ^{17}Ne. Very recently halo properties were also observed for ^{22}C [5] and ^{31}Ne [6]. Halo nuclei are characterized by a very small nucleon separation energy, s or p wave valence nucleons, few-body clusterization and their extraordinary large size. A halo structure gives many interesting features to a nuclear reaction, such as an extremely large interaction cross section and a very narrow parallel momentum distribution for the core fragment compared with its neighboring nucleus, a very large Coulomb excitation cross section due to pygmy dipole resonances (PDR), a strong coupling between various reaction channels including continuum states, and so on (see Ref. [2] and references therein). The study of halo structure and properties will remain one of the most fascinating topics of nuclear physics.

α clustering is a popular phenomena in heavy nuclei and in highly excited states of $N{=}Z$ nuclei. In past decades it has been found that a cluster structure develops in very neutron rich unstable nuclei even at or close to the ground state [3, 7]. Excess neutrons tend to play the role of a chemical bond to stabilize the nucleus in a molecular configuration. Furthermore even a chain or ring configuration was predicted for a nuclide composed of many α clusters and valence neutrons [8]. Various theoretical models have been developed to describe cluster formation and decay [9–11]. Effort has also been made to incorporate the single-particle degree of freedom and the cluster degree of freedom into one theoretical framework [3]. A clustering effect also appears between valence neutrons. For a two neutron halo nucleus, the di-neutron

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configuration may be built on a certain nuclear matter density provided by the core fragment [12–14]. Strong neutron coupling is also predicted for heavy nuclei due to the so called size effect [15]. Neutron coupling has attracted wide interest since it is related to BCS and BEC pairing crossover and the possible BES condensation in neutron matter.

Although theoretical work has been largely advanced over past years, experimental investigation of the cluster structure of unstable nuclei is still very limited, especially for ground and low-lying excited states. Reaction tools are especially useful here due to the short life time and the absence of the decay γ ray. We describe here the knockout reaction mechanism which has been the most powerful tool in extracting halo and cluster structure information from unstable nuclei. Also some care will be paid to the newly developed “towing mode” reaction tool.

2 Development with knockout reaction

Knockout reaction played important role in probing the single-particle as well as cluster structure of stable nuclei [16]. Since the application of fast radioactive nucleus beams, a knockout reaction with inverse kinematics has been developed into a powerful tool for spectroscopic investigation of exotic nuclei [17]. This reaction is characterized by the removal of part of the projectile while leaving the remaining part untouched as a perfect spectator. The latter then carries the original structure information of the projectile to be detected at forward angles.

In the beginning, only the number of spectator fragments was detected which allows us to deduce the total interaction cross section [18]. Later on the method to detect the parallel momentum distribution of the spectator fragments was developed based on the use of a dispersion-matched magnetic spectrograph[17]. This distribution, together with the in-beam γ-ray detection, allows us to make a spectroscopic analysis of the selected single particle state [19]. If the spectator of a knockout reaction is a resonance state, the corresponding spectroscopic factor (SF) may also be obtained from the reconstructed relative energy spectrum [20].

But as indicated on many occasions (Ref. [21] for instance), the applicability of the reaction tools to extract nuclear structure information depends sensitively on the correct and precise understanding of the reaction mechanisms. Recently it was reported that, for nuclei with large neutron-proton asymmetry, the SF obtained from knockout reactions deviates systematically from those obtained from transfer reactions [21]. Also a suspicious resonance peak at around 0.6 MeV above the ground state of ^{7}He was reported from a knockout reaction experiment using a carbon target but cannot be confirmed by many other experiments [20]. These kinds of puzzles call for a better handling of the knockout reaction mechanism.

Early in 1990s the knockout reaction mechanism of a fast moving Borromean type projectile was sketched into four classes [22, 23]: (A) sudden breakup of the projectile nucleus in the field provided by the target nucleus (diffractive breakup); (B) knockout of a valence nucleon followed by sudden breakup of the spectator fragment; (C) knockout of a valence nucleon followed by strong final state interaction (FSI or resonance decay), and (D) knockout of the core fragment (cluster) followed by emission of valence nucleons with FSI. In subsequent studies using a knockout reaction it was realized that mechanism (C) is dominating (B) [24], whereas class (D) was often ignored based on the strong absorption assumption for experiments employing complex targets (such as Beryllium or Carbon targets) and measuring only the spectator fragments at forward angles [17]. Later on it was demonstrated in a quasi-free scattering experiment with ^{6,8}He beams impinging on a non-absorptive Hydrogen target [25], the coincident measurement of the forward moving fragment together with the recoiled target proton allows us to clearly identify the process (D), which in turn could be used to study the cluster structure of the projectile at ground state, similar to the traditional (p, pα) experiment with normal kinematics for studying stable nuclei [16]. This is of great importance since the clustering phenomenon seems to be growing at the neutron drip-line, and spectroscopic investigation of this new degree of freedom is urgently needed [3]. The reported experiment was carried-out at very high energy (717 and 671 MeV/u for ^{6}He and ^{8}He, respectively) and without implementation of neutron detection. It would be interesting to investigate if this recoiled proton tagging method was also valid at energies of around 100 MeV/u where most knockout reaction experiments for unstable nuclei were performed and a lot of spectroscopic information was generated. This study of the reaction mechanism, together with neutron detection, might also shed light on the puzzles concerning the SF for the asymmetric system and the reconstructed resonance peak as mentioned above.

3 Criteria for a clean knockout

To validate the knockout reaction concept, it is required that the collision between the target and the constituent of the projectile obeys the quasi-free condition so that the remaining part of the projectile behaves like a good spectator. It is then mandatory to make the reaction mechanism related kinematics analysis in order to design a sensitive experiment. In the case with recoiled proton tagging we have developed a formula to be used for quantitative evaluation [26]. Assuming that projectile A is composed of B and C (A=B+C) and B makes a quasi-free collision with the target (a proton target for example), according to momentum conservation the magnitude of the momentum of the recoiled proton $p_{\rm p}$ in the laboratory system is equal to that transferred to constituent B, the latter is exactly the same as the relative momentum $p_{\rm B,rel}$ of B seen in the projectile rest frame. After the sudden collision, B tends to leave spectator C by overcoming the attraction force between them and will lose part of its momentum according to:

$$\begin{aligned}\Delta p_{\rm B,rel} &= \int f{\rm d}t = \int \frac{{\rm d}\Phi}{{\rm d}r}{\rm d}t = \int \frac{{\rm d}\Phi}{v_{\rm r}} \\ &\approx \frac{m_{\rm B}S_{\rm B}}{p_{\rm B,rel}} = \frac{m_{\rm B}S_{\rm B}}{p_{\rm P}}\,({\rm for}\ \Delta p_{\rm B,rel} \ll p_{\rm P})\,. \quad (1)\end{aligned}$$

Where f is the interaction force along the direction of the field gradient, Φ the potential between B and C, and $S_{\rm B}$ the separation (or binding) energy of the B+C system. The quasi-free condition is equivalent to require that the momentum loss of B leaving remnant C is much smaller than the momentum it acquired from the sudden collision ($\Delta p_{\rm B,rel} \ll p_{\rm p}$). It is evident that this condition is better satisfied for higher momentum transfer $p_{\rm p}$, lighter knockout component (B) and smaller banding energy $S_{\rm B}$. We note that $p_{\rm p}$ is a function of recoiled proton emission angle with respect to the beam axis. A smaller proton angle, corresponding to a smaller impact parameter, would lead to a larger $p_{\rm p}$ value. We empirically set the ratio $R = \Delta p_{\rm B,rel}/p_{\rm p} < 0.15$ as a quasi-free collision condition. This criteria should be verified by experimental observation as outlined below. In addition the influence of $\Delta p_{\rm B,rel}$ on the emission angle of spectator C may also be checked. As a matter of fact, since force f acts between constituents B and C, the momentum of C ought also change by the same quantity of $\Delta p_{\rm B,rel}$ relative to its original momentum in the projectile. The transverse component of $\Delta p_{\rm B,rel}$ divided by the incident parallel momentum of C gives the deviation angle of C. This deviation angle must be substantially smaller than the scattering angle of B. Otherwise the C component would stick on B, contradicting the knockout concept.

For the GSI experiment with 717 MeV/u ^{6}He and 671 MeV/u ^{8}He impinged on proton target, the above criteria is satisfied even at angles very close to 90° [25]. But at medium energy such as about 80 MeV/u [26], proton detection must be moved to some smaller angles, especially where core fragment knockout is concerned. We plot in Fig. 1 the calculation of the ratio R as a function of the recoiled proton angle relative to the beam axis, for knockout of the ^{6}He core fragment from a ^{8}He projectile at 80 MeV/u. The requirement of R<0.15 would put an upper limit of about 62° for the recoiled proton angle. According to this estimation we see that the quasi-free feature of the knockout reaction can well be retained at around 100 MeV/u, as long as the projectile is loosely bound and the recoiled proton angle is limited to an appropriate range. We should note that the detection of protons at medium energy is much easier than at very high energy, due to the penetrability of the particle. This is one of the advantages of performing experiments at medium energies.

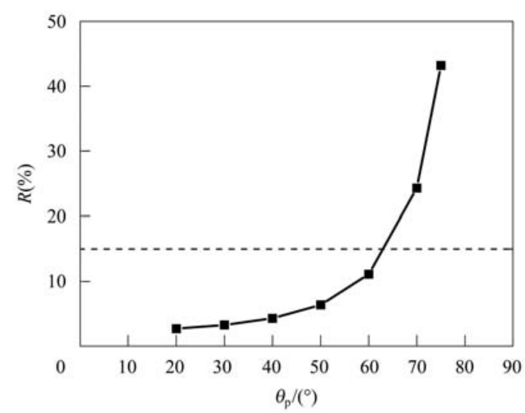

Fig. 1. The ratio R, defined in the text, is plotted as a function of the recoiled proton angle relative to the beam axis for knockout of the ^{6}He core fragment from a ^{8}He projectile at 80 MeV/u. The 0.15 requirement for R corresponds to a an upper limit of the recoiled proton angle at about 62°.

4 Discrimination of the knockout reaction mechanisms

As indicated above, recoiled proton tagging may provide a good way to discriminate the core fragment and valence nucleon knockout mechanisms. This discrimination was initially realized at very high energy [25]. Fig. 2 shows the polar angle correlation between the recoiled protons and the α-core fragments, detected in an knockout reaction experiment induced by ^{6}He at 717 MeV/u on a proton target. As explained above, the proton detection was set very close to 90°. Two components appear in the Figure, one with larger proton and ^{6}He angles corresponding to core knockout mechanism, whereas the other has smaller angles corresponding to valence nucleon knockout. These mechanisms were verified by other quantities, such as azimuthal angle correlation, energy-angle correlation, differential cross section and so on [25].

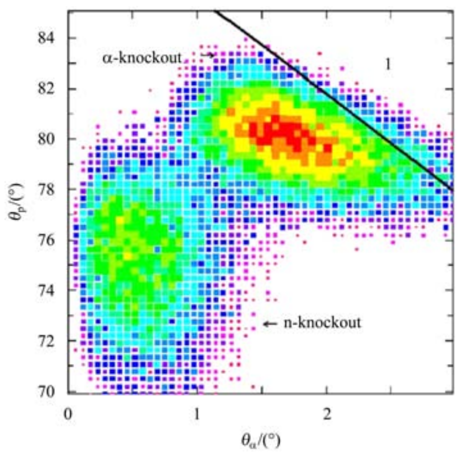

Fig. 2. Correlation between the polar angles of the recoiled protons and the α-core fragments in the knockout reaction induced by 717 MeV/u ^{6}He on proton target.

The same kind of discrimination may also be realized at much lower energies, such as at around 80 MeV/u as demonstrated by our recent experimental data [26]. Based on the above kinematic analysis, proton detection now must move to a smaller angular region, as shown in Fig. 3. We note that the distribution in Fig. 3 is just preliminary by using only the signals taken by the CsI(Tl) crystals in particle telescopes. Much finer presentation will be obtained by using Silicon strip detector information. Verifications with other quantities are also successful, supporting the validity of quasi-free knockout at the medium energy around 100 MeV/u and the applicability of the recoiled proton tagging technique.

Discrimination of knockout reaction mechanisms is not only important for its own sake but also for the correct spectroscopic investigation of the relevant structure configuration. For instance, by selecting pure valence nucleon knockout events the single-particle state (either bound or resonant state) can be probed without contamination from other reaction mechanisms. On the other hand, by selecting the core fragment knockout events the cluster structure at ground state may be analyzed quantitatively [26]. In addition, after the core knockout, the correlation between the remaining valence neutrons may be studied by directly detecting the emitted neutrons. All of these topics are actually very interesting and experiments of these kinds are highly demanding.

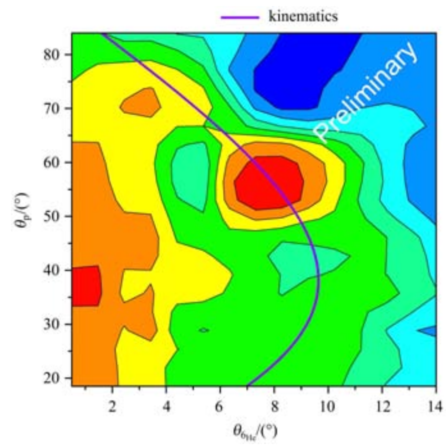

Fig. 3. Correlation between the polar angles of the recoiled protons and the ^{6}He-core fragments in the knockout reaction induced by 82.3 MeV/u ^{8}He.

5 The towing mode reaction

A knockout reaction is effective at relatively high energies, typically above 50 MeV/u [17]. Another well known spectroscopic tool is the transfer reaction which is effective at around fermi energy, namely 10–30 MeV/u [27]. In between these energy regions a new mode of direct nuclear reaction, the so called "towing mode" reaction, was discovered [28, 29] and gradually applied to extract the single particle and cluster structure SF for both stable and unstable nuclei [30–33].

The towing phenomenon was observed when carrying out a heavy ion collision experiment at around 40 MeV/u. By selecting events with one light particle emission together with the ejectile and target nucleus staying basically at their ground or low-lying excited states, the emission may be treated as a direct towing process. If we call the mother nucleus of the emitted particle the emitter, the collision counterpart the probe, the "towing" mode is characterized by emitting the particle to the same side of the probe with a relatively large emission angle and rapidity. This is in contradiction to the knockout process in which the knocked out particle and the probe nucleus go to the opposite sides of the beam axis. It has been demonstrated that the angular and energy (or momentum vector) distributions of the towed particle depend sensitively on its original quantum state in the mother nucleus (emitter), providing a good spectroscopic tool to extract the structural information of the emitter. It is understandable that "towing" could only happen within an energy window. It will switch to a knockout process when the energy is higher or merged into a transfer or collective excitation process when the energy is lower down to fermi energy range.

A simple but effective theoretical tool has been developed corresponding to the "towing" process [29]. The emitted particle is supposed to move in time-dependent two center nuclear potentials provided by the emitter and the probe, respectively. The calculation is done in the framework of a Time-Dependent Schrodinger Equation (TDSE) with a structure wave function as its input.

This experimental method together with the theoretical model has been applied to investigate the structure of exotic nuclei such as ^{11}Be [30]. It was also exercised to study the di-neutron configuration of a borromean type halo nucleus by using the towing mode breakup reaction [32], and a theoretical tool for two particle emission was also implemented accordingly [31]. More amazingly the cluster SF at ground state can also be extracted by properly towing the cluster out of its mother nucleus [33]. Based on systematic development over a decade or so, we anticipate that the "towing mode" reaction will become an complementary spectroscopic tool at transition energies with important applications.

6 Summary

Halo and cluster structures at the ground states of unstable nuclei are among the most fascinating phenomena of current nuclear physics. Much effort has been made to observe and describe these exotic structures. From an experimental point of view, the selection of a proper reaction tool is mandatory in order to extract the correct structure information. In the past twenty years the knockout reaction has been used intensively to investigate the structure of unstable nuclei in a spectroscopic way, thanks to the development of an inverse kinematics technique together with the implementation of dispersion-matched magnetic spectrograph and in-beam γ detection. However, some ambiguities still exist which require a more precise understanding of various knockout processes. In this report we have illustrated the latest development towards this purpose and have given emphasis to a proton tagging method together with quantitative criteria to assure the quasi-free feature of knockout process. The newly developed "towing mode" reaction tool is also outlined and its applicability at transit energies is discussed. We did not discuss another well known spectroscopic tool, the transfer reaction, due to its requirement for an intense beam and complex channel coupling with many input parameters, which are often not available in the field. Of course, the transfer reaction might be very important in some specific cases, especially for light exotic nuclei and at relatively low energies.

References

1 Hamamoto I. J. Phys. G, 2010, **37**: 055102
2 Ershov S N et al. Phys. G, 2010, **37**: 064026
3 Horiuchi H. J. Phys. G, 2010, **37**: 064021
4 Baye D et al. Nucl. Phys. News, 2004, **15**: 10
5 Tanaka K et al. Phys. Rev. Lett., 2010, **104**: 062701
6 Nakamura T et al. Phys. Rev. Lett., 2009, **103**: 262501
7 Oertzen W V et al. Phys. Rep., 2006, **432**: 43
8 Funaki Y et al. J. Phys. G, 2010, **37**: 064012
9 Taniguchi Y et al. Phys. Rev. C, 2009, **80**: 044316
10 QI C, XU F R et al. Phys. Rev. Lett., 2009, **103**: 072501
11 DONG T, REN Z Z. Phys. Rev. C, 2010, **82**: 034320
12 Hagino K et al. Phys. Rev. Lett., 2007, **99**: 022506
13 Khoa D T, Oertzen W V. Phys. Lett. B, 2004, **595**: 193
14 YE Y et al. J. Phys. G, 2005, **31**: S1647
15 Hagino K et al. J. Phys. G, 2010, **37**: 064040
16 Roos P G et al. Phys. Rev. C, 1977, **15**: 69
17 Hansen P G, Tostevin J A. Annu. Rev. Nucl. Part. Sci., 2003, **53**: 219
18 Tanihata I, Hamagaki H, Hashimoto O et al. Phys. Rev. Lett., 1985, **55**: 2676–2679
19 Dickhoff W H, J. Phys. G, 2010, **37**: 064007
20 Aksyutina Yu et al. Phys. Lett. B, 2009, **679**: 191
21 Suzuki Y, Lovas R G, Yabana K, Varga K. Structure and Reaction of Light Exotic Nuclei. Taylor and Francis, London, 2003
22 Korsheninnikov A A, Kobayashi T. Nucl. Phys. A, 1994, **567**: 97
23 Korsheninnikov A A et al. Europhys. Lett., 1995, **29**: 359
24 Nilsson T et al. Nucl. Phys. A, 1996, **598**: 418
25 Chulkov L V, Aksouh F, Bleile A et al. Nucl. Phys. A, 2005, **759**: 43
26 YE Y L et al. Nucl. Phys. A, 2010, **834**: 454c
27 Oganessian Y T, Zagrebaev V I. Phys. Rev. C, 1999, **60**: 044605
28 Scarpaci J A, Beaumel D, Blumenfeld Y et al. Phys. Lett. B, 1998, **428**: 241
29 Lacroix D, Scarpaci J A, Chomaz P. Nucl. Phys. A, 1999, **658**: 273
30 Lima V, Scarpaci J A, Lacroix D et al. Nucl. Phys. A, 2007, **795**: 1
31 Assie M, Lacroix D. Phys. Rev. Lett., 2009, **102**: 202501
32 Assie M, Scarpaci J A, Lacroix D et al. Eur. Phys. J. A, 2009, **42**: 441
33 Scarpaci J A, Fallot M, Lacroix D et al. Phys. Rev. C, 2010, **82**: 031301