Recoil proton tagged knockout reaction for $^8$He

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We report for the first time the discrimination of the core fragment knockout and valence nucleon knockout reaction mechanisms at medium energy range, by the use of the recoil proton tagging technique. Intense $^8$He beams at 82.3 MeV/u were supplied by the RIPS beam line at RIKEN, and impinged on both hydrogen and carbon targets. Recoil protons were detected in coincidence with the forward moving core fragments and neutrons. The core fragment knockout mechanism is identified through the polar angle correlation and checked by various kinematics relations. This mechanism may be used to extract the cluster structure information of unstable nuclei. On the other hand, with the selection of the tagged valence nucleon knockout mechanism, a narrower peak of $^7$He ground state is obtained. The extracted neutron spectroscopic factor $S_n = 0.512(18)$ is relatively smaller than the no-tagged one, and is in good agreement with the prediction of $ab\text{ initio}$ Green’s function Monte Carlo calculations.

1. Introduction

Knockout reactions play an important role in probing the single-particle and cluster structure of stable nuclei [1,2]. Since the advent of fast radioactive nuclear beams, knockout reactions with inverse kinematics have been developed into a powerful tool for spectroscopic investigation of the exotic properties of unstable nuclei [3]. As indicated in many occasions (Ref. [4] for instance), applicability of reaction tools to extract nuclear structure information depends sensitively on the precise handling of the reaction mechanisms. Recently it was reported that, for nuclei with large neutron–proton asymmetry, the spectroscopic factors (SF) obtained from knockout reactions deviate systematically from those obtained from transfer reactions [5,6]. Some non-direct reaction processes were proposed to account for this discrepancy [7]. 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 [8,9], but cannot be confirmed by some other experiments (see Ref. [10] for a summary) including a similar knockout reaction experiment but using a hydrogen target [11]. It seems better to use “a clean structure-less probe” like proton target in order to avoid the possible complex reaction processes [11]. But even for a proton target various reaction mechanisms together with their sensitivities to particular structure configurations still need to be clarified.

$^8$He is an exotic nucleus with the largest neutron to proton ratio for any known particle-stable nucleus, and has attracted continuous attention experimentally as well as theoretically [12]. Based on the already established important properties [8,10–12], $^8$He provides an excellent test case to evaluate the reaction mechanisms. Early in 1990s the breakup reaction mechanisms of a fast moving Borromean type projectile was classified as [13,14]: (A) sudden breakup of the projectile nucleus in the field provided by the target nucleus (diffractive breakup); (B) knockout of a valence nucleon (stripping) 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 followed by emission of valence nucleons. In the subsequent studies using knockout reactions it was realized that, for a Borromean nucleus, the mechanism (C) dominates over (B) [15]. In the mean time the process (D) was often ignored based on the strong absorption assumption for experiments employing composite targets [3]. This assumption, which neglects the effect of the complex core–target interactions, is necessary to validate

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the inclusive experiment measuring the spectator core fragments at forward angles (some times in coincidence with the in-beam γ-rays). But in the case of proton target this strong absorption assumption is obviously not valid and the explicit treatment of the process (D) is needed. We note that an important step towards the isolation of a typical reaction process was reported based on the exclusive measurement of the two breakup components of a proton-rich projectile [16]. But the purpose of that experiment was to separate the diffractive breakup (process (A)) from the stripping (process (B) or (C)), without touching process (D) due to the application of an absorptive 9Be target.

As demonstrated in a quasi-free scattering (QFS) experiment with 6He beams impinging on a hydrogen target [17], the core fragment knockout process (process (D)) can be isolated through the exclusive measurement of the recoil target protons in coincidence with the forward moving core fragments. In addition the SF of the cluster structure of the projectile in its ground state can be extracted from this core knockout process. This is of great importance since clustering structure seems growing in the vicinity of the neutron drip-line and spectroscopic investigation of this new degree of freedom is very demanding [18]. The reported experiment was carried out at very high energies (671 MeV/u for 6He) and did not employ neutron detection [17]. It would be interesting to investigate the separability and applicability of these reaction mechanisms at energies around 100 MeV/u where most knockout experiments for unstable nuclei have been performed and a lot of spectroscopic information has been accumulated [6].

2. Description of the experiment

A detailed description of the experiment was given in a recent article reporting the results of quasi-elastic scattering of 6He [19], and only a brief outline relevant to the knockout reaction is presented here. The experiment was carried out at the RIKEN-RIPS beam line [20]. The secondary beam of 6He at 82.3 MeV/u was produced by a 115 MeV/u 12C primary beam impinged on a thick 9Be target. The secondary beam intensity amounts to 2.5 × 10^6 pps with a purity of about 70% for 6He. A schematic view of the detection setup is given in Fig. 1. A CH2 foil (83.0 mg/cm^2) and a carbon film (133.9 mg/cm^2) were mounted as the physics targets, together with an empty target used for background measurement. Drift chambers (BDC1, BDC2 and MDC) were used upstream and downstream from the target to determine the particle tracks event by event, with an angular resolution of less than 0.1°. A deflection magnet was installed downstream from the target in order to keep the forward neutron wall away from being exposed to the direct beam. Another drift chamber (FDC) was installed down stream from the magnet to measure the deflected tracks of the charged fragments. An hodoscope wall composed of seven plastic scintillation bars (HODO) was placed behind the Magnet + FDC system to measure the time of flight (TOF) and energy loss of the fragments. Neutron walls composed of 60 scintillation bars were mounted at about 5 meters downstream from the target around the 0° axis (beam direction). Two specially designed telescopes (D11 and D12) were installed, covering an angular range between 15° and 75° (for two setups) relative to the beam axis, to detect the recoil protons [21]. Another telescope D2 was installed beside the magnet acceptance, covering forward angles from 6° to 21°. Each of these telescopes is composed of one double-sided silicon strip detector (DSSD) of 1 mm in thickness and 64 × 64 mm^2 in area, one large surface silicon detector of 1.5 mm in thickness, and one or two layers of thick CsI(Tl) crystals. The strip width of the DSSD is 2 mm at both X and Y directions.

3. Results and discussion

3.1. Knockout of the core fragment

Plotted in Fig. 2(a) and (b) are polar angle correlations between the recoil protons and the forward moving 6He fragments, for CH2 and carbon targets, respectively. For ease of comparison Fig. 2(a) and (b) are drawn with comparable number of incident particles and target thickness. At the upper right part of Fig. 2(a) a component (in the frame F) arises clearly with relatively large proton and 6He polar angles and follows quite well the 6He + p free scattering kinematics as displayed by the solid curve. The angular spreading (and the width of the frame) of this component is mainly determined by the transverse momentum distribution of the 6He core fragment [17]. According to earlier studies [17] this component corresponds to the core fragment knockout mechanism, whereas the component at very small 6He angles (in the frame N) is related to the valence nucleon knockout mechanism. For the core knockout component (frame F) the upper limit of the proton angle is due to the angular coverage of the D2 telescope as specified above, whereas the lower limit at about 35° is due to the rapid decrease of the knockout cross section as illustrated below. We note that the medium energy range of 50–100 MeV/u is already at the fringe of the quasi-free knockout reaction domain. At these energies the proton detection angular window must be selected carefully in order to observe the core fragment knockout component, as illustrated in Fig. 2(a).

Fig. 1. Schematic view of the experimental setup at RIKEN-RIPS. Beams were injected from the lower left corner.
Fig. 2. Polar angle correlations between the recoil protons and the forward moving $^6$He fragments for (a) CH$_2$ target and (b) carbon target, measured in the experiment using $^8$He beam at 82.3 MeV/u. The solid curve is the kinematics relation for $^6$He + p free scattering at 82.3 MeV/u. The frames with dashed line denote the event selection for the core fragment knockout (frame F) and the valence neutron knockout (frame N), respectively.

We have further checked the relation between the $^6$He energy versus its emission angle. It turns out that for each angular bin the energy distribution is well peaked and the peak moves as a function of the angle according to approximately the free scattering kinematics, as shown in Fig. 3. This angular correlation between the core fragments and the recoil protons also satisfies well the condition of quasi-free core–target collision. We may therefore conclude that, by using the recoil proton tagging technique, the $^6$He core fragment knockout reaction mechanism can well be identified for $^8$He + p collision at about 80 MeV/u.

It is interesting to see in Fig. 2 that the core fragment knockout component (frame F) is almost free from carbon target contamination, implying that CH$_2$ target here behaves like a “pure” hydrogen target as long as the recoil proton tagging is used and the cluster knockout process is concerned. This is interesting since in many circumstance it would be easier to manipulate a solid CH$_2$ target instead of a pure liquid or ice hydrogen target.

The polar angle correlation and the kinematics conditions were also checked for $\alpha$ core fragments of the $^8$He projectiles. Although general trends for free scattering are still satisfied, the distributions of the $\alpha$ core fragments show clear offsets from the free scattering kinematics. This effect was also observed in the high energy experiment [17], where 8 MeV dynamic separation energy is needed to describe the behavior of the $\alpha$ core within the $^8$He mother nucleus, much higher than the static separation energy of about 3 MeV. This excess binding effect was explained by possible substructures of the 4n system within the $^8$He, which needs to be proved by further studies. Due to this kinematics deviation from the free scattering, we do not make further quantitative analysis for the $\alpha$ core knockout process.

Based on the quasi-free scattering mechanism for $^6$He core fragment, the absolute differential cross sections can be deduced accordingly. The solid angle for the coincident detection was determined by Monte Carlo simulation taking into account the two-body scattering kinematics, the realistic incident particle momentum distribution and the actual detector setup and efficiency [19]. The results are shown in Fig. 4 as the filled diamonds. For comparison the $^6$He elastic scattering data reported earlier [22] are also plotted in the figure as the open circles. We note that at energies of a few tens of MeV/u, the elastic scattering differential cross sections at medium angular range for $^8$He are slightly below those for $^6$He [13]. Therefore even though we did not measure the $^8$He elastic scattering in the present experiment due to the limited deflection power of the magnet, we may expect that $^8$He elastic scattering cross sections are about an order of magnitude smaller than $^6$He core fragment knockout cross sections within the selected angular range.

As adopted in Ref. [17], a simple and approximate way to extract the SF for a cluster configuration is to...
compare the measured cluster knockout cross sections to the calculated elastic scattering ones. As displayed in Fig. 4 by the dashed line, Glauber model calculations were performed for \(^6\)He + p elastic scattering. Here the matter radii of \(^6\)He was adjusted to 2.8 fm to fit the experimental data. A good description (solid curve) for the knockout data can also be obtained by just reducing the matter radii of \(^6\)He to 2.2 fm. This simple treatment lends a further support to the quasi-free feature of the cluster knockout mechanism. The shrinking of the \(^6\)He core cluster inside a \(^4\)He nucleus was also suggested previously [17], with the similar reduction of the radii. Since there is no need to substantially shift the absolute value of the calculated cross section to meet the experimental data, the SF of \(^6\)He cluster configuration in \(^4\)He should be close to 1.0. This is comparable to the previously reported value of 1.3 obtained from the high energy experiment with the same manner of analysis [17]. Of course more sophisticated calculations, such as those with impulse approximation [2], should be performed in order to extract the cluster SF with higher precision.

We note also the spectrum in Fig. 2(b), in which correlations between the recoil protons and the forward emission \(^6\)He fragments for carbon target are shown. Protons here must have originated from the carbon target since all protons in the projectile were taken away by the forward moving \(^6\)He fragments. It is clear that some severe reaction processes, such as charge-exchange and fragmentation of the carbon target [23], might have occurred in addition to the direct knockout. These complex reaction processes should be addressed further with special attention paid to their effects on the extraction of SF. For the present work we just use the carbon target for background subtraction purpose only.

3.2. Knockout of the valence neutron and the reconstruction of \(^7\)He resonance

Now we select events with small \(^6\)He polar angles detected by the magnet system and related to the valence neutron knockout mechanism as illustrated by the frame N in Fig. 2. The corresponding transverse momentum acceptance of the magnet system was limited to about ±130 MeV/c for \(^6\)He, which is large enough to accept all fragments resulted from valence neutron knockout reactions [17]. The momenta of the fragments and neutrons were determined from their emission angles and TOF values. \(^6\)He + n relative energy \((E_{fn})\) spectrum can then be reconstructed according to the standard invariant mass method [11].

For the sake of comparison we firstly do not apply recoil proton tagging. The results for proton target are obtained from the spectrum for CH\(_2\) target subtracted by that for carbon target, normalized to the same number of incident particles and the same carbon thickness. The acceptance of the whole detection system as a function of \(E_{fn}\) was deduced by Monte Carlo simulation taking into account the decay kinematics including p-wave asymmetry [8] and the actual detector geometry and efficiency. In Fig. 5 is shown by the filled circles the reconstructed \(E_{fn}\) spectra corrected by the acceptance. The error bars on the data points are statistical only. In addition, about 12% systematic error on the cross sections should be considered, including uncertainties in particle identification, target thickness, number of incident particles, drift chamber and neutron detector efficiencies, and simulation of the energy response function and the acceptance for \(E_{fn}\) reconstruction.

The \(E_{fn}\) spectrum can be described by a single Breit–Wigner shape function [11]:

\[
\frac{d\sigma}{dE_{fn}} \propto \frac{\Gamma(E_{fn})}{[E_r + \Delta(E_{fn}) - (E_{fn})]^2 + \frac{1}{4} \Gamma_{fn}^2(E_{fn})}.
\]

In the formula \(E_r\) is the resonance energy above the \(^6\)He + n separation threshold and \(\Gamma\) the resonance width given by \(\Gamma = 2P_l(E_{fn})\gamma^2\) with \(P_l(E_{fn})\) the penetrability function and \(\gamma^2\) the reduced width [24]. \(\Delta(E_{fn})\) is the resonance shift determined by \(\Delta(E_{fn}) = -[S_l(E_{fn}) - B]P_l(E_{fn})\) the shift function and \(B\) the boundary condition chosen according to \(\Delta(E_r) = 0\). The theoretical function was convoluted by the energy response function of the detection system and then fitted to the experimental data. The energy response function has approximately a Gaussian shape with its width deduced from the reconstruction formulas [25,8] and related to the detection resolutions of \(^6\)He energy, neutron energy and neutron–\(^4\)He opening angle [21]. The width (standard deviation) increases from about 100 keV at \(E_{fn}\) of 0.25 MeV to about 400 keV at \(E_{fn}\) of 3.5 MeV. \(\chi^2\) fits were performed to determine the best values of the parameters and the corresponding statistical errors [11].

The optimized calculation for hydrogen target is displayed in Fig. 5 by the thin solid curve, and the corresponding parameters are listed in Table 1 labeled “H–no tag”. The standard statistical uncertainties are recorded in the parenthesis. \(S_{fn}\) in the table is the neutron SF deduced from \(S_{fn} = \gamma_{obs}^2/\gamma_{sp}^2\) with \(\gamma_{obs}^2\) obtained from the above fit to the experimental data and \(\gamma_{sp}^2 = 1.504\) MeV the theoretical value adopted in Ref. [11] for a channel radius \(R = 4.0\) fm. In addition to the statistical errors shown in the table, systematical uncertainties of about ±23 keV for the resonance position and about ±29 keV for the resonance width should be

![Fig. 5. \(^6\)He + n relative energy spectra measured in the knockout reaction induced by \(^6\)He at 82.3 MeV/u impinging on a hydrogen target (filled circles). The filled diamonds are the results with the recoil proton tagging. The error bars are statistical only. The curves represent the fits explained in the text.](image-url)

Table 1

| Exp. | \(R\) fm | \(E_f\) MeV | \(\Gamma(E_f)\) MeV | \(P_l(E_f)\) | \(S_l(E_f)\) | \(\gamma_{obs}^2\) MeV | \(S_{fn}\) |
|------|---------|-------------|------------------|-------------|-------------|-----------------|------|
| H-p tag | 4       | 0.430(3)    | 0.182(5)         | 0.118       | −0.778      | 0.770(24)       | 0.512(18) |
| H-no tag | 4      | 0.380(2)    | 0.195(4)         | 0.101       | −0.799      | 0.970(15)       | 0.645(15) |
considered, originated mainly in uncertainties in determining the flight path length of $^6$He fragments and in the detector response function.

As indicated above recoil proton tagging might allow a better selection of the valence neutron knockout mechanism. Reconstructed $E_{fn}$ spectrum subjected to the proton tagging is now shown in Fig. 5 by the filled diamonds with an arbitrary unit. Although the tagged spectrum agrees in general with the n-tagged one, the former shows a clearly narrower peak. Especially the lower $E_{fn}$ side of the peak displays a sharper increase. It should be noted that this relative narrowing effect must be related to the recoil proton detection since all other conditions were the same for both spectra which are built from events in the same $^6$He+n measurement. Without the proton tagging, one of the possible mixing mechanisms is the inelastic excitation and subsequent decay of the $^8$He projectile, characterized by two neutrons emitted to forward angles. As demonstrated earlier [15] and proved by our data analysis, reconstructions by randomly using one of the $^8$He decay neutrons may contribute to less than 10% of the $E_{fn}$ spectrum at the peak area of the $^7$He ground state. But this background spectrum extents more to the lower $E_{fn}$ side, leading to an increase of the cross section for a few mb. It is evident that proton tagging with relatively large momentum transfer allows to remove this inelastic scattering contamination. Another possible source of this narrowing effect might be the restriction on recoil proton detection. We have checked the reconstructed $E_{fn}$ spectrum by applying different cutoffs on proton angle, but no statistically meaningful differences on resonance peak position or resonance width were identified. This means the current tagged results are “stable” for quite wide recoil proton angular (momentum) range. But low energy protons close to 90 degrees were not detected in the present experiment due to the energy threshold of D1 telescope (about 13 MeV). These low energy protons at large angles, corresponding to knockout neutrons emitted to small angles, are related more probably to multiple scattering processes, especially at incident energies below 100 MeV/u, as illustrated theoretically in Ref. [27]. In future experiments it would be interesting to extend the light charged particle measurement to larger angular coverage and with much lower energy detection threshold, in order to clarify various processes which might affect the resonance reconstruction and the SF extraction.

Parameters resulted from the fit to the tagged data with the B-W formula are listed in Table 1 labeled “H-p tag”. The $S_n$ for the ground state of $^3$He is now 0.512, which is in good agreement with the value of $S_n(3/2^-) = 0.527(4)$ predicted by the $ab\initio$ Green's function Monte Carlo (GFMC) calculations [26,29]. Considering the systematic uncertainties our results are in agreement with those obtained from also a knockout reaction experiment but at a higher energy of 240 MeV/u [11]. As references we note also $S_n$ results of 0.64(9) from the $^7$Li(d,$^2$He) reaction [26] and 0.36(7) from the $^8$Li(d,$^3$He)$^7$He(3/2−) transfer reaction [28].

Applicability of the proton tagging technique depends also on the achievable tagging efficiency. For the present experimental setup the event number obtained with the proton tagging is about one twentieth of that measured inclusively. Since the average azimuthal angle covered by D11 and D12 proton telescopes is only about one twelfth of $2\pi$, proton tagging with full azimuthal angle coverage may lead to roughly 60% event counting compared to inclusive measurement, indicating a reasonably high tagging efficiency.

4. Summary and conclusion

Application of the proton target in knockout reaction is of the advantage to avoid some complex interaction processes related to the composite target. But since the usual strong absorption assumption is no longer valid for a proton target, the core-target collision should be treated explicitly. In the present work we demonstrate that, based on careful selection of the detection angular window and weakly bound object, the recoil target protons provide a good means to discriminate the core fragment knockout and the valence nucleon knockout reaction mechanisms, at medium energies around 100 MeV/u.

In our experiment induced by intense $^8$He beam at 82.3 MeV/u, the recoil protons were measured in coincidence with the forward moving core fragments and neutrons. The $^8$He core fragment knockout mechanism is identified by the polar angle correlation and further checked by other kinematics conditions. This process can be used to extract the spectroscopic information of the cluster structure of unstable nuclei in their ground state. On the other hand the valence nucleon knockout mechanism may also be selected and applied to extract single-particle structure information. In the case of $^7$He ground state, a narrower peak was obtained with the proton tagging, resulting in a relatively smaller neutron SF of 0.512(18). This narrowing effect encourages more investigations of possible complex processes eventually being involved in knockout reactions, especially at incident energies below 100 MeV/u, and to identify certain tagging methods to discriminate these processes.

It is also shown that CH$_2$ target may be used in place of “pure” hydrogen target as long as the recoil proton tagging is applied and the core fragment knockout process is concerned. In order to further explore the recoil proton tagging technique, high efficiency proton detection system with large solid angle coverage should be implemented.

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