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Three-body breakup of ^{6}He and its halo structure

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ABSTRACT

The Borromean halo nucleus ^{6}He has been studied by a kinematically complete measurement of Coulomb and nuclear breakup into $\alpha + 2n$ on Pb and C targets at 70 MeV/nucleon. Fully quantum-mechanical four-body breakup calculations reproduce the energy and angular differential cross sections below $E_{\mathrm{rel}} \sim 1$ MeV for both targets. The model used here reproduces the ^{6}He ground-state properties as well as α-n and n-n scattering data and predicts an average opening angle $\langle\theta_{nn}\rangle$ of 68° between the two halo neutrons. However, the model underestimates the breakup cross sections for higher E_{rel}, indicating a possible contribution from the inelastic breakup. Alternatively, we examine the empirically modified calculations that reproduce the energy-differential cross sections for a wide range of scattering angles for both targets. The extracted $B(E1)$ peaks at $E_{\mathrm{rel}} \sim 1.4$ MeV and amounts to 1.6(2) e^2 fm^2 for $E_{\mathrm{rel}} \leq 20$ MeV, resulting $\langle\theta_{nn}\rangle = 56^{+9}_{-10}$ degrees. In either interpretation, the current results show evidence of the dineutron spatial correlation in ^{6}He.

Neutron halo is an intriguing quantum tunneling phenomenon observed in nuclei when we approach the neutron dripline. The extended spatial distribution of the halo neutron(s) induces large interaction cross section [1], narrow core momentum distribution [2,3], and enhanced electric dipole strength, $B(E1)$, at low excitation energies (E_x) $\sim$ 1 MeV, known as the soft $E1$ excitation [4–13]. Recent high-lights for halo nuclei are the observation of deformation-driven halo in the island-of-inversion region, for instance ^{29}Ne [14], ^{31}Ne [15], and ^{37}Mg [16]. Extensive experimental efforts have also been devoted to the Borromean $2n$-halo nuclei, such as ^{6}He [5,17–29], ^{11}Li [2–4,11,30–38], ^{14}Be [39,40], ^{17,19}B [41–47] and ^{22}C [48–50], where any of the two-body constituent subsystems are unbound but the whole three-body system is bound. One of the important questions regarding the Borromean $2n$-halo nuclei is if the two halo neutrons are correlated and spatially compact as "dineutron" [51–53]. Such dineutron structure was first predicted by A. B. Migdal as appearing on the nuclear surface [51] although this has not yet been established experimentally. So far, such dineutron correlation has been hinted in the $2n$ transfer [22,26], the Coulomb breakup [11,47] and the charge radius measurements [33]. Very recently, the quasi-free neutron knockout reaction also showed the existence of the dineutron in ^{11}Li [54].

The large soft $E1$ excitation strength for the $1n$-halo nuclei, originating from the long tail of the halo wave function, has been understood as having a nonresonant character [6–10,12]. However,

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despite considerable experimental and theoretical efforts, the $E1$ excitation of the Borromean $2n$-halo nuclei is still elusive [13]. The observed $E1$ excitation of ^{11}Li from the Coulomb dissociation that peaks at $E_x \sim 0.6$ MeV [11] is understood as a nonresonant enhancement from direct breakup, while low-lying dipole resonances located at $E_x \sim 1$ MeV were recently identified in the (d, d') [37] and (p, p') [38] reactions. The $B(E1)$ distributions of ^{6}He from two previous experiments at 240 MeV/nucleon at Gesellschaft für Schwerionenforschung (GSI) [5] and at 23.9 MeV/nucleon at Michigan State University (MSU) [23] are not consistent with each other. Further studies are needed to reach a unified understanding of the two-neutron correlations as well as the breakup mechanism of Borromean nuclei.

Among all the known Borromean nuclei, ^{6}He is the lightest and simplest that can be treated as α+n+n. The α core is nearly inert due to its large neutron and proton separation energies of about 20 MeV and no bound excited states. The ground state of ^{6}He has been extensively studied both experimentally and theoretically. The bulk properties, such as mass [28], charge radius [24,25,28] and matter radius [55–57], have been measured with high precision. The neutron knockout reactions showed that the valence-neutron configuration of ^{6}He is dominated by $(p_{3/2})^2$ with small mixtures of $(p_{1/2})^2$ around 7% [19,21] and $(s_{1/2})^2$ in the level of 5–10% [27,29]. Theoretically, ^{6}He has been intensively studied using the α+n+n three-body models [58–69], in which the αn and nn interactions are known with little ambiguity [70–72]. We note that due to the small number of nucleons, *ab initio* type calculations of ^{6}He are also available [73–76]. As such, the spectroscopy of ^{6}He is of great importance since this can provide a stringent test for those advanced theories in order to assess the two-nucleon and three-nucleon interactions and many-body correlations at extreme isospin conditions. We should also note that the dynamical process such as breakup reactions can now be studied microscopically for the Borromean $2n$-halo nuclei using the advanced four-body CDCC (continuum-discretized coupled-channels) method [77,78].

This Letter reports the kinematically complete measurements of Coulomb and nuclear breakup reactions of ^{6}He on Pb and C targets at 70 MeV/nucleon with much higher statistics than previous works. We show here the first full microscopic analysis of the ^{6}He breakup reactions using the state-of-the-art CDCC calculations at intermediate energies, so that one can now discuss the Borromean structure of ^{6}He and its breakup dynamics consistently.

The experiment was performed at the RIKEN Accelerator Research Facility. A secondary ^{6}He beam was produced through fragmentation of a 100 MeV/nucleon ^{18}O primary beam on an 8 mm thick ^{9}Be target and purified using the RIKEN Projectile Fragment Separator [79]. The ^{6}He momentum acceptance was set 0.1%, where purity of 96% and intensity of $\sim 3\times10^4$ pps were achieved. The ^{6}He particles were identified event-by-event using the energy loss (ΔE) and time of flight (TOF) information. The ^{6}He beam, tracked by two beam drift chambers (BDCs), then bombarded a 783 mg/cm^2-thick natural Pb target or a 347 mg/cm^2-thick C target, with mid-target energy of 70 MeV/nucleon. The empty-target run was also performed to measure the background events generated by other beam-line materials instead of the target, which were then subtracted in the offline analysis.

The current experimental setup was nearly identical to the one adopted in the ^{11}Li Coulomb breakup measurement [11], except that we did not measure the γ-rays as α has no bound excited states. The charged fragments following the breakup reaction were bent by a dipole magnet and tracked by two drift chambers (MDC and FDC) located upstream and downstream of the magnet. A plastic scintillator array (HOD) consisting of seven 1 cm thick plastic scintillator slats was used to measure the ΔE and TOF of the fragments. Particle identification was performed by combining the ΔE, TOF with the magnetic rigidity information from the tracking. The momentum of the fragments was deduced from the TOF as well as the tracking results of the BDCs and MDC. The neutrons were detected by a plastic scintillator array called NEUT consisting of two detector walls called NEUT-A and NEUT-B. [11]. Each wall of NEUT consisted of two adjacent layers of plastic scintillator bars, each of which was coupled to two photonmultiplier tubes at both ends to record both the timing and the charge signals. The front surface of NEUT-A and NEUT-B was located at 4.684 m and 5.872 m respectively, downstream of the target, covering an angular range from $-8.0°$ to $+17.5°$ in the horizontal direction and $\pm 4.4°$ in the vertical direction. A thin layer of plastic veto detectors located in front of NEUT-A were used to reject charged particle background. Total $1n$ detection efficiency of 23.0(11)% and TOF resolution of $\sigma \sim 450$ ps were obtained, using the ^{7}Li(p,n)^{7}Be(g.s.+0.43 MeV) reaction. In the case of two-neutron detection for Borromean nuclei, rejection of cross-talk signals caused by neutron scattering is required [11,80]. In the present work, the cross-talk rejection procedures detailed in Ref. [11] were applied. We note that the present experimental setup was sufficiently sensitive to the decay of ^{6}He at low excitation energies down to the α+n+n decay threshold, as demonstrated in Fig. 1 of Ref. [11].

Table 1
Inclusive two-neutron removal cross sections of ^{6}He on Pb and C targets compared with previous data measured at different incident beam energies [5,23].

Energy (MeV/nucleon)	Pb(^{6}He, α)X (mb)	C(^{6}He, α)X (mb)	Ratio
23.9 [23]	1700(100)	360(25)	4.7(4)
70 (present)	1184(64)	242(10)	4.9(2)
240 [5]	1150(90)	190(18)	6.1(7)

The inclusive two-neutron removal cross sections σ_{-2n}[1] of ^{6}He on Pb and C targets were first examined and compared in Table 1 with previous works at different incident beam energies. The quoted errors of σ_{-2n} from present work include both the statistical (3%) and the systematic (4% for the Pb target, 3% for the C target) errors, with the latter mainly originating from the acceptance correction. The current σ_{-2n} on the C target is higher than that at 240 MeV/nucleon [5], and smaller than that at 23.9 MeV/nucleon [23], consistent with the energy dependence of σ_{-2n} from the eikonal model calculations [81,82]. σ_{-2n} on the Pb target are about 5 times larger than those on the C target for all the three energies. Such a large factor shows the dominance of electromagnetic dissociation process for ^{6}He breakup on a high-Z target, as expected for halo nuclei [2].

The experimental differential cross sections as a function of the α-n-n relative energy ($E_{\rm rel}$) and the scattering angle in the center-of-mass frame ($\theta_{\rm cm}$) are shown in Fig. 1. The integrated cross sections are 1105 ± 19 (stat) ± 87 (sys) mb ($E_{\rm rel} \leq 6$ MeV, $\theta_{\rm cm} \leq 7°$) and 115 ± 3 (stat) ± 9 (sys) mb ($E_{\rm rel} \leq 6$ MeV, $\theta_{\rm cm} \leq 10°$) for Pb and C targets, respectively. The quoted systematic uncertainties arise mainly from the estimation of the two-neutron detection efficiency. The experimental spectra were compared to four-body CDCC calculations that treats both nuclear and Coulomb breakup processes simultaneously. In the calculations, the ground state of ^{6}He was described within a three-body model as detailed in Ref. [67], which reproduces the $2n$ separation energy, the matter and charge radii of ^{6}He. The scattering wave functions of ^{6}He were expanded by a series of wave functions including the ground- and discretized continuum states obtained using the pseudostate discretization method [83,84]. We employed the KKNN [70] and the

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[1] Here and in Ref. [23], σ_{-2n} is the inclusive cross section of ^{6}He → α + X, where we do not consider any conditions for neutrons, and was denoted as $\sigma_{\rm sum}$ in Ref. [5]. σ_{-2n} in Ref. [5] was used as the $2n$-removal cross section where the two neutrons were both out of the acceptance of the neutron detectors.

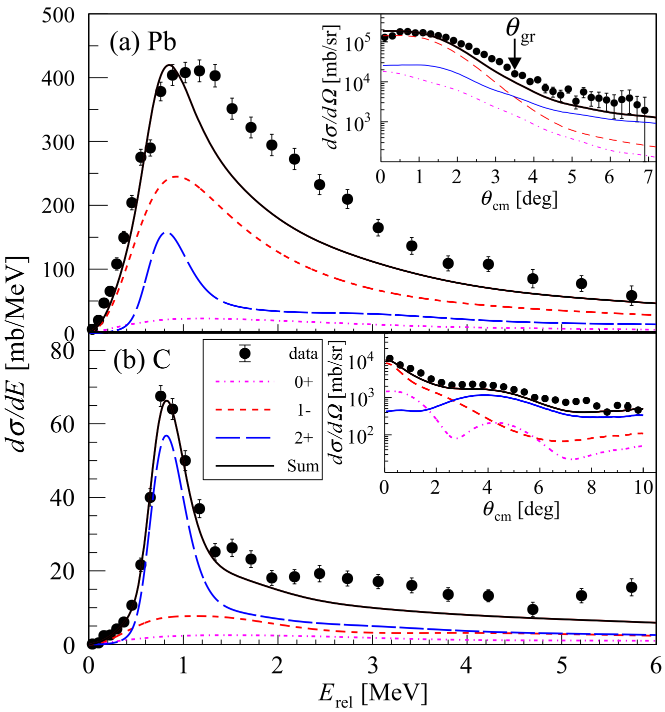

Fig. 1. Breakup cross sections as a function of the three-body relative energy for (a) ^{6}He + Pb with $\theta_{\rm cm} \leq 7°$ and (b) ^{6}He + C with $\theta_{\rm cm} \leq 10°$. The insets show the scattering angular distributions in the center-of-mass frame of ^{6}He + target. $\theta_{\rm gr}$ denotes the grazing angle of 3.45°. The data is compared with the four-body CDCC calculations (black solid lines) decomposed to 0^{+} (magenta dotted-dash lines), 1^{-}(red dashed lines) and 2^{+} (blue dashed lines) continuum states.

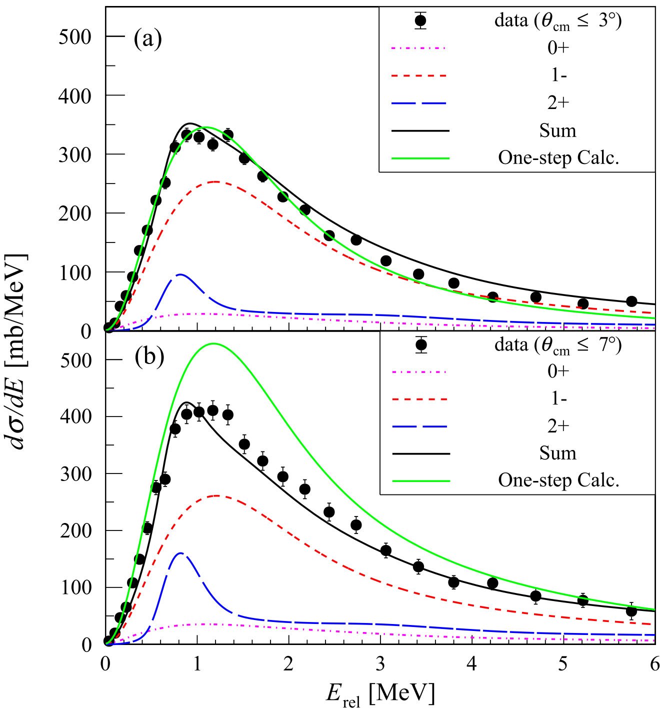

Fig. 2. Breakup cross sections as a function of the three-body relative energy for ^{6}He + Pb with angular cuts of (a) $\theta_{\rm cm} \leq 3°$ and (b) $\theta_{\rm cm} \leq 7°$. The data is compared with the "modified CDCC" calculations. See text for details.

Minnesota [71,72] potentials for the internal αn and nn interactions, respectively, which reproduce the corresponding scattering data. The double folding model was adopted to construct the optical potentials for the n-target and α-target systems using the JLM effective nucleon-nucleon interactions [85]. It is known that the normalization factor for the imaginary part of the JLM interaction, $N_{\rm I}$, is required [86–88]. Here, $N_{\rm I}$ is chosen to be 0.1 and a reasonable variation of $N_{\rm I}$ from 0.1 to 0.6 affects the cross sections at forward angles only slightly, less than 10% for $E_{\rm rel} \leq 1$ MeV. The calculation incorporated 0^{+}, 1^{-}, 2^{+} continuum states, while 3^{-} state was found negligible.

As shown in Fig. 1, the CDCC calculations reproduce well the differential cross sections for C and Pb targets below $E_{\rm rel} \sim 1$ MeV, while the cross sections at higher excitation energies are underestimated. Note that theoretical curves have been convoluted with the experimental resolutions.[2] The breakup cross sections for the C target are dominated by a narrow peak located at $E_{\rm rel} \sim 0.85$ MeV, coinciding with the known 2^{+}_{1} state of ^{6}He with excitation energy of $E_x = 1.8$ MeV [89] ($E_x = E_{\rm rel} + S_{2n}$, where $S_{2n} = 975.46(23)$ keV [28]). The good reproduction of the data indicates that the nuclear breakup effects are well controlled in the current CDCC calculations. The Pb target data shows a large bump at low relative energies just above the $2n$ breakup threshold, a characteristic feature inherent to neutron halo, known as soft $E1$ excitation. The multipole decomposition of the calculation shows that the cross sections are dominated by the excitation to the 1^{-} state, as expected. Around the peak, however, also the 2^{+} contribution is found to be important. The calculations underestimate the cross sections at higher excitation energies, probably due to the missing of the inelastic breakup processes, such as the target excitation. In this case, such contributions must be subtracted first in extracting the $B(E1)$ distribution from the experimental breakup cross sections. Accordingly, the $B(E1)$ distribution will be represented by the result of the three-body model adopted in the calculation (see solid black line in Fig. 3).

As an alternative scenario, we may tune the three-body model Hamiltonian to reproduce the measured breakup cross sections, assuming that the experimental data purely correspond to the elastic breakup events. To do this, we modify the 1^{-} states of ^{6}He via changing the α-n interaction and introduce a multiplying factor to the coupling between the 0^{+} and 1^{-} states. The value of the multiplying factor and its associated uncertainty were obtained based on χ^2 minimization. The CDCC calculation with this empirically modified model is referred to as "modified CDCC". As shown in Fig. 2, the modified CDCC results in a slightly broader 1^{-} component comparing with the original calculation in Fig. 1. The calculations reproduce consistently the experimental breakup cross sections for a wide range of different angular cuts ($\theta_{\rm cm} \leq \theta_{\rm cut}$, with $3° \leq \theta_{\rm cut} \leq 7°$). Fig. 2 shows two representative cases of $\theta_{\rm cut} = 3°$ and 7°, where the former $\theta_{\rm cut}$ is close to the grazing angle of $\theta_{\rm gr} = 3.45°$. We also compare the data to the one-step Coulomb breakup calculations that do not consider nuclear breakup and multi-step effects. The one-step calculations overestimate the cross sections for $\theta_{\rm cut} = 7°$, while they agree with the data in addition to the modified CDCC calculation for $\theta_{\rm cut} = 3°$. This agreement is due to the fact that the nuclear breakup effect offsets the multi-step effect for $\theta_{\rm cm} \leq 3.0°$, in which the former increases the cross section while the latter decreases it. We found that such agreement is obtained only in the angular range of $\theta_{\rm cut} = 3°$–$4°$. The effects of multi-step and nuclear breakup are found strong in ^{6}He, even in some range of $\theta_{\rm cut} < \theta_{\rm gr}$, which is different from the situation in ^{11}Li where $\theta_{\rm cut}$ below $\theta_{\rm gr}$ worked for extracting the Coulomb one-step component [11]. As such, we adopt here a different approach to extract $B(E1)$ empirically using the modified CDCC.

The $B(E1)$ extracted using the modified CDCC for the current data is shown in Fig. 3, where it is compared with the $B(E1)$ evalu-

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[2] The energy resolutions (1σ) have the form of $\Delta_{E_{\rm rel}} = 0.027 + 0.177 \times E_{\rm rel}^{0.654}$ MeV for the Pb target and $\Delta_{E_{\rm rel}} = 0.016 + 0.151 \times E_{\rm rel}^{0.655}$ MeV for the C target.

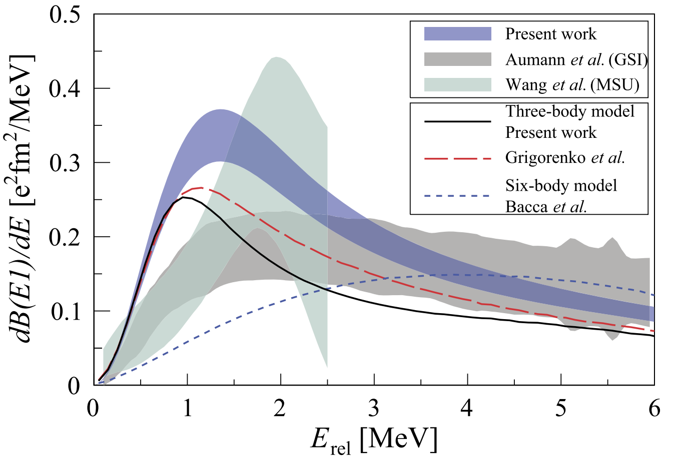

Fig. 3. The B(E1) distribution obtained by the present work compared with previous results from GSI [5] and MSU [23]. The experimental B(E1) distributions are also compared with the three-body calculations (black solid line from this work, red dashed line from Ref. [90]) and *ab initio* six-body calculation (blue dotted line) [91].

ations from the previous experiments [5,23]. The current $B(E1)$ distribution has been determined to reproduce the energy-differential breakup cross sections consistently for $\theta_{\rm cut}$ from 3 to 7 degrees. The error band arises mainly from the estimation of the parameters in the modified CDCC (7%) and the two-neutron detection efficiency (8%). Our $B(E1)$ distribution shows a low-energy bump at $E_{\rm rel} \sim 1.4$ MeV, being shifted ~0.5 MeV lower than the MSU result which has large statistical uncertainty. The low-energy bump was missing in the GSI result. Above 2 MeV, the current and the GSI data exhibit consistently considerable strength extending to higher excitation energies.

The energy-integrated $B(E1)$ strength is obtained to be 1.1(1) e^2 fm^2 for $E_{\rm rel} \le 6$ MeV. This value is consistent, but with better precision, compared to the previous GSI result of 0.87(26) e^2 fm^2 (see Fig. 4 in Ref. [5]). The current result in terms of Weisskopf unit is 5.2(5) W.u., nearly as large as the so-far strongest case of ^{11}Li (~4.5 W.u., for $E_{\rm rel} \le 3$ MeV) [11], demonstrating the soft-$E1$ excitation characteristics of ^{6}He. The $B(E1)$ spectrum of ^{6}He is much broader compared to the spectrum of ^{11}Li that peaks at very low relative energies around 0.3 MeV [11]. This could be due to the different $(s_{1/2})^2$ probabilities in their ground states and the different core-n final-state interactions [92,93].

Comparing with theoretical predictions, the three-body model used in our original CDCC calculations (black solid line) reproduces the present d$B(E1)$/dE below $E_{\rm rel} \sim 1$ MeV, while it underestimates the strength at higher excitation energies, as expected from Fig. 1(a). It is interesting to note that a very recent three-body calculation by Grigorenko et al. [90] (red dashed line), that may have improved the older results by Danilin et al. [61], also reproduces the current d$B(E1)$/dE below $E_{\rm rel} \sim 1$ MeV. We also compare our $B(E1)$ distribution to the *ab initio* six-body calculation [91,94] employing the Argonne two-nucleon potential AV4′ [95]. However, this calculation does not show any low-energy bump at $E_{\rm rel} \sim 1$ MeV. This indicates that the missing components in AV4′, such as the tensor and spin-orbit forces, could play a significant role in describing photoabsorption of the Borromean system. It is thus desirable that full *ab initio* calculations be performed in the near future to assess the nucleon-nucleon and three-nucleon forces at extreme neutron-to-proton ratios. Note also that the present results would also serve as a benchmark for a wide range of few-body calculations dealing with the electric response of ^{6}He, for instance the models in Refs. [58–60,63–66,69,77,96–100].

We now extract the geometrical information on the three-body structure of ^{6}He. First, one can extract the mean-square distance between the α core and the center-of-mass of the two halo neutrons, $\langle r^2_{c-2n}\rangle$, as the non-energy weighted $E1$ cluster sum rule shows that this distance is proportional to the total integrated $B(E1)$ strength [101,102]:

$$B(E1) = \int_{-\infty}^{+\infty} dE \frac{dB(E1)}{dE} = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \langle r^2_{c-2n}\rangle. \tag{1}$$

When we adopt the modified CDCC estimation, the integrated $B(E1)$ strength up to $E_{\rm rel} \le 20$ MeV amounts to 1.6(2) e^2 fm^2. We thus obtained $\sqrt{\langle r^2_{c-2n}\rangle} = 3.9(2)$ fm. In the three-body model of $2n$-halo nuclei, the core-$2n$ distance is related to the mean-square distance between the two halo neutrons, $\langle r^2_{nn}\rangle$, by [103–105]

$$\langle r^2_m\rangle = \frac{A_{\rm core}}{A}\langle r^2_m\rangle_{\rm core} + \frac{2A_{\rm core}}{A^2}\langle r^2_{c-2n}\rangle + \frac{1}{2A}\langle r^2_{nn}\rangle, \tag{2}$$

where A is the mass number of the halo nucleus (namely 6 in this case) and $\langle r^2_m\rangle$ is the mean-square matter radius. The root-mean-square matter radii of α and ^{6}He are 1.463(6) fm and 2.49(4) fm, respectively, deduced from the charge-radius measurement [106], the interaction cross section [17,107] and the elastic scattering data [57]. We thus extract the value of $\sqrt{\langle r^2_{nn}\rangle} = 4.1(7)$ fm for ^{6}He. Note that this value is smaller than the value of 5.9 ± 1.2 fm obtained using two-neutron interferometry technique [108], which is more sensitive to the populated continuum states instead of the ground state configurations [109]. Combining the core-$2n$ distance and n-n distance, we obtain the mean n-n opening angle of $\langle\theta_{nn}\rangle = 56^{+9}_{-10}$ degrees. The extracted opening angle is significantly smaller than the average opening angle of 90° for two noncorrelated neutrons. This indicates that ^{6}He has a sizable dineutron correlation.

We should note that the modified CDCC assumes a three-body model adjusted to reproduce the breakup data without incorporating inelastic breakup effects, such as the target excitation. As mentioned, the original CDCC calculation shown in Fig. 1, which uses the exact interactions between the constituent two-body systems, underestimates the breakup data for $E_{\rm rel}$ >1 MeV. The reason could be attributed to the missing of the inelastic effects in the calculation. If it is the case, there is still a possibility that the true $B(E1)$ distribution is closer to the black solid line in Fig. 3, where slightly smaller dineutron correlations are predicted ($\langle\theta_{nn}\rangle = 68°$). Evaluating the $B(E1)$ differences between the exact three-body calculation and the empirical one extracted with modified CDCC is an open question for future experimental and theoretical works.

In summary, we have performed the Coulomb and nuclear breakup of ^{6}He on Pb and C targets at 70 MeV/nucleon. State-of-the-art four-body CDCC calculations reproduce the obtained energy and angular differential cross sections below $E_{\rm rel} \sim 1$ MeV for both targets. However, the calculations underestimate the cross sections at higher excitation energy region, probably due to the missing of inelastic breakup processes. In such case, our data would support the adopted three-body model in the calculation, which predicts an average opening angle of 68° between the two halo neutrons relative to the α core. Alternatively, we assume that there is no inelastic contribution in the experimental data and empirically modify the CDCC calculations to reproduce the energy-differential breakup cross sections for a wide range of different angular cuts. The extracted $E1$ strength of ^{6}He peaks at about $E_{\rm rel} = 1.4$ MeV and amounts to 1.6(2) e^2 fm^2 for $E_{\rm rel} \le 20$ MeV. Applying the non-energy weighted cluster sum rule, the average opening angle between the two halo neutrons relative to the α core is evaluated as 56^{+9}_{-10} degrees. Either interpretation shows the opening angle is significantly smaller than the non-correlated angle of 90 degrees, revealing the existence of the dineutron spatial correlation in the ground state of the halo nucleus ^{6}He.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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