Observation of Strong Low-Lying $E1$ Strength in the Two-Neutron Halo Nucleus ^{11}Li

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An exclusive measurement has been made of the Coulomb dissociation of the two-neutron halo nucleus ^{11}Li at 70 MeV/nucleon at RIKEN. Strong low-energy (soft) $E1$ excitation is observed, peaked at about $E_x = 0.6$ MeV with $B(E1) = 1.42(18)$ e^2 fm^2 for $E_{\rm rel} \leq 3$ MeV, which was largely missed in previous measurements. This excitation represents the strongest $E1$ transition ever observed at such low excitation energies. The spectrum is reproduced well by a three-body model with a strong two-neutron correlation, which is further supported by the $E1$ non-energy-weighted cluster sum rule.

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^{11}Li is an intriguing atomic nucleus, exhibiting a two-neutron halo structure that extends well beyond a ^{9}Li core and with a radius comparable to that of ^{208}Pb [1–4]. The nucleus has attracted much attention as a novel "Borromean" quantum three-body bound system, where its two-body subsystems, two neutrons and ^{10}Li, are both unbound. A melting of the $N = 8$ magic number, whereby the $0p_{1/2}$ and $1s_{1/2}$ orbitals are nearly degenerate, is also suggested in ^{11}Li [5,6]. Despite considerable theoretical and experimental efforts, the characteristic nature of the two-neutron correlation, three-body binding mechanism, and the origin of the shell melting in this nucleus are still uncertain.

Strong soft electric dipole ($E1$) excitation is a unique phenomenon of halo nuclei, where significant $E1$ transition strength [$B(E1)$] shows up at low excitation energies (E_x): of order 1 MeV [7–18]. This is in sharp contrast to the $E1$ response of normal nuclei that is dominated by the giant dipole resonance at $E_x = 10$–20 MeV. One of the long-standing issues in ^{11}Li is how the soft $E1$ excitation arises and can be explained in terms of its characteristic halo/Borromean structure. Although the direct measurements of the $B(E1)$ distributions of ^{11}Li made at 28 MeV/nucleon at Michigan State University (MSU) [13], at 43 MeV/nucleon at RIKEN [14], and at 280 MeV/nucleon at Gesellschaft für Schwerionenforschung (GSI) [15] provided a qualitative confirmation of the strong soft dipole excitation in ^{11}Li, the observed $B(E1)$ distributions are neither conclusive nor consistent (see also Fig. 3). Differences of strengths between Refs. [13,15] are more than a factor of 2 at low relative energies ($E_{\rm rel}$). A two-peak structure was suggested in Ref. [15] but not from the other analyses.

As a result of this unsettled experimental situation, we lack a complete understanding of the nature of the soft $E1$ excitation of the two-neutron halo nucleus ^{11}Li. Experiments performed on other two-neutron halo nuclei ^{6}He [16,17] and ^{14}Be [18] also involved large uncertainties. As theoretical work on ^{11}Li has demonstrated [19–30], a precise determination of the soft $E1$ excitation spectrum would place significant constraints on the reaction mechanism, two-neutron correlation, core-n correlation, and the shell melting in the ^{11}Li ground state.

The present Letter reports the results of a new and significantly improved measurement of the low-lying $B(E1)$ distribution of ^{11}Li, thereby resolving the ambiguous experimental situation. With much higher statistics and careful treatment of two-neutron events, we have significantly enhanced the experimental sensitivity at low relative energies: down to $E_{\rm rel} = 0$ MeV in the three-body breakup channel. This has revealed considerable low-lying strength, which was hitherto inaccessible, experimentally. The observed low-lying $E1$ strength in ^{11}Li is shown to provide invaluable information on the two-neutron correlation in the halo.

The essential ingredient of the present experiment is a kinematically complete measurement of the momentum vectors of the ^{11}Li projectile and of the three outgoing particles: ^{9}Li and two neutrons. The latter are produced with a velocity close to the ^{11}Li projectile in the breakup reaction on a Pb target and are emitted in a narrow cone in the forward direction. Momentum vectors of the outgoing particles are used to reconstruct the invariant mass of the ^{11}Li excited state, which is then translated into the relative energy of ^{9}Li + n + n. The ^{11}Li + Pb scattering angle $\theta_{\rm cm}$ in their center-of-mass frame is determined from the opening angle between the momentum vector of ^{11}Li and the sum of the outgoing momentum vectors. Possible γ ray emission from excited states of the daughter nucleus ^{9}Li was also monitored.

The Coulomb dissociation of ^{11}Li was measured at the RIKEN Accelerator Research Facility using a secondary ^{11}Li beam produced from the fragmentation of 100 MeV/nucleon ^{18}O on a thick Be target. The ^{11}Li ions were separated using the RIKEN projectile-fragment separator [31] and focused onto a secondary Pb target of 346 mg/cm^2, with a typical intensity of 2×10^4 ions/sec. The average energy of ^{11}Li at the center of the target was 69.7 MeV/nucleon with a momentum spread of $\pm 3\%$.

The main elements of the experimental setup around the secondary target are shown in Fig. 1(left). The coincidence momentum measurement of the projectile and the three outgoing particles was made using a nearly identical setup and the same procedures as described in Ref. [12] for the Coulomb breakup of ^{11}Be, except for the following two points. First, we employed 36 blocks of NaI(Tl) scintillators [detector array for low-intensity radiation (DALI)], which surrounded the target, to measure γ rays from ^{9}Li ejectiles. Since no significant γ line was observed in coincidence with the two neutrons, we confirmed that the ^{9}Li was produced in its ground state. Hereafter, we neglect the production of ^{9}Li in an excited state. Second, we configured the neutron detector setup for unambiguous two-neutron detection by adopting a configuration of two detector walls, where 54 sets of plastic scintillator rods were installed into two layers, NEUT-A [2 rods (D) $\times$ 12 rods (V)] and NEUT-B [2 rods (D) $\times$ 15 rods (V)] separated by 1.09 m. Each rod had dimensions of 214 cm (H) $\times$ 6.1 cm (V) $\times$ 6.1 cm (D) and was coupled to photomultiplier tubes at each end. To avoid ambiguities caused by γ rays, a high energy threshold of 6 MeVee (electron equivalent) was imposed.

In the present analysis, where accurate two-neutron detection was essential, special care was taken to exclude cross-talk events caused by the scattering of a single neutron producing two independent signals. We thus demanded the following causality condition for those events in which we observe one hit in NEUT-A and another in NEUT-B (different-wall events). The cross-talk events are fully excluded by discarding all events with $\beta_A \geq \beta_{AB}$, where β_A denotes the velocity between the target and NEUT-A and β_{AB} the apparent velocity between NEUT-A and NEUT-B. This exclusion method was possible because of ample statistics, even though it sacrifices about half of the true (non-cross-talk) different-wall events. The advantage of this scheme is that the detection efficiency has a smooth dependence on E_{rel} and maintains sufficient magnitude over the low-energy region of interest, down to $E_{rel} = 0$ MeV, as shown by a solid histogram in Fig. 1(right). We examined the effectiveness of the technique in a separate calibration experiment using the ^{7}Li$(p, n)^{7}$Be reaction at 70 MeV, where only one neutron is emitted, and confirmed that mistakenly identified cross-talk events were negligible. The total $1n$ detection efficiency was also determined from this calibration as 23.4%. In the analysis, we also include same-wall events where two neutrons hit the same wall. In this case, events where the two neutrons are very close together had to be discarded, to remove cross talk, resulting in a dip in the efficiency curve at $E_{rel} = 0$ MeV [Fig. 1(right)]. Nevertheless, we confirmed that the efficiency-corrected energy spectrum for these same-wall events is identical to that for the different-wall events.

Figure 2 shows the differential cross sections ($d\sigma/dE_{rel}$) of the ^{11}Li Coulomb dissociation for the angular range $0 \leq \theta_{cm} \leq 5°$. The error bars are purely statistical and do not include the estimated 12% systematic error in the absolute normalization coming primarily from uncertainties in the neutron detection efficiency. A pronounced peak at very low relative energies, near 0.3 MeV, is observed. The integrated cross section is large, $2.34 \pm 0.05(\text{stat}) \pm 0.28(\text{syst})$ b, for $E_{rel} \leq 3$ MeV.

To extract the $B(E1)$ distribution $[dB(E1)/dE_{rel}]$, we combine $d\sigma/dE_{rel}$ with the angular distribution, as displayed in the inset in Fig. 2. We note that, in the semiclassical framework, the scattering angle for pure Coulomb dissociation is related to the impact parameter $b = a \cot(\theta_{cm}/2)$, where a denotes half the distance of closest approach in the classical head-on collision. As was ob-

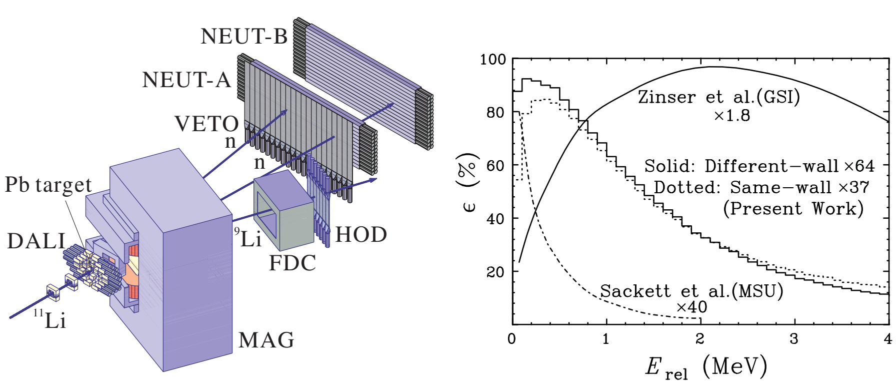

FIG. 1 (color online). Left: A schematic view of the experimental setup, which contains a dipole magnet (MAG), drift chamber (FDC), hodoscope (HOD), and two walls of neutron detector arrays (NEUT-A,B). Right: Efficiency curves for the different-wall (solid histogram) and same-wall events (dotted histogram), compared with those from GSI [15] and MSU [13].

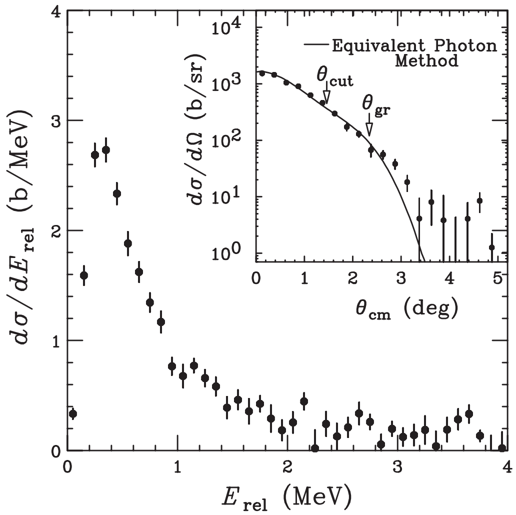

FIG. 2. Breakup cross sections for [11]Li + Pb at 70 MeV/nucleon as a function of the three-body relative energy for data with $\theta_{cm} \leq 5°$. Inset: Angular distribution of [11]Li (the [9]Li + n + n c.m.) scattered by the Pb target in the range $0 \leq E_{rel} \leq 4$ MeV. θ_{gr} denotes the grazing angle (2.34°). The calculation using the equivalent photon method is shown by the solid curve.

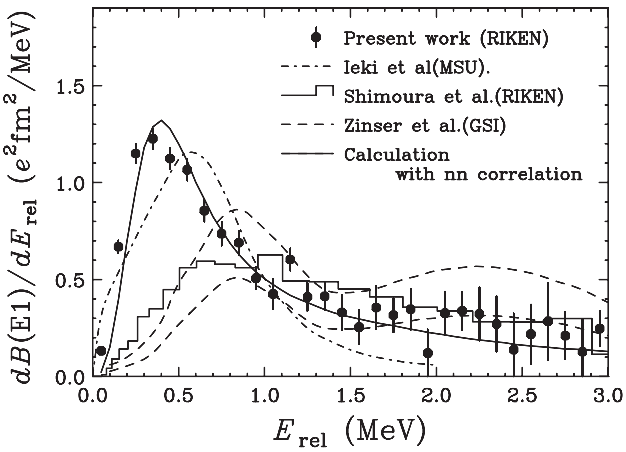

FIG. 3. The $B(E1)$ distribution obtained in the present work (solid circles) is compared with those from previous measurements [dotted-dashed line [13], solid histogram [14], dashed lines (zone) [15]]. The present data are also compared with the calculation (solid line) [20] which included the full n-n correlation.

served in the Coulomb breakup of [11]Be [12], there is strong enhancement of the [11]Li breakup yield at very forward angles. We have selected the angular region with $\theta_{cm} \leq \theta_{cut}(= 1.46°)$, corresponding to $b \geq 20$ fm, where first-order $E1$ Coulomb breakup dominates. The agreement with a pure $E1$ excitation calculation, shown by the solid curve, supports this assumption.

The $B(E1)$ value is obtained, for these angle-selected data, by using the equivalent photon method [32,33] described by

$$\frac{d^2\sigma}{d\Omega_{cm} dE_{rel}} = \frac{16\pi^3}{9\hbar c} \frac{dN_{E1}(\theta_{cm}, E_x)}{d\Omega_{cm}} \frac{dB(E1)}{dE_{rel}}, \qquad (1)$$

where $N_{E1}(\theta_{cm}, E_x)$ denotes the number of virtual photons with photon energy E_x at scattering angle θ_{cm}. Applying this relation, with the photon number integrated over the selected angular range, the resulting $B(E1)$ distribution is shown by the solid circles in Fig. 3. In this procedure, the integration included the experimental angular resolution of 0.44° (1σ). To obtain the photon energy E_x ($=E_{rel} + S_{2n}$), we adopted $S_{2n} = 300$ keV from the 2003 mass evaluation [34]. Using the preliminary but more precise value of $S_{2n} = 376 \pm 5$ keV [35], the $B(E1)$ value is enhanced by about 6%.

Figure 3 compares the present $B(E1)$ distribution with the previous three data sets. Our new result reveals substantial $E1$ strength that peaks at very low relative energies around 0.3 MeV. This feature is in sharp contrast to the previous data, which showed more reduced strength at low energies. The present result also exhibits considerable strength extending to the higher energy region of a few MeV. This behavior of the $B(E1)$ distribution leads to a large energy-integrated $B(E1)$ strength of 1.42 ± 0.18 $e^2\,fm^2$ [4.5(6) Weisskopf units], for $E_{rel} \leq 3$ MeV, which is the largest soft $E1$ strength ever observed for atomic nuclei.

The difference of the present $B(E1)$ distribution from those of earlier analyses is attributed to our enhanced sensitivity to low relative energies below $E_{rel} = 0.5$ MeV compared to previous experiments, as is indicated in the efficiency curves of the current and GSI experiments [15] in Fig. 1(right). Inefficiency at low relative energies was also suggested for the previous RIKEN data where a cut for low [9]Li-n relative velocities was necessary due to non-availability of a magnetic spectrometer at that time [14]. As for the MSU result, there is no obvious reason for inefficiency at low relative energies, although much reduced efficiencies are apparent at E_{rel} above 2 MeV, as shown in Fig. 1(right). A possible explanation of the reduced strength below $E_{rel} = 0.5$ MeV from the MSU data may be the importance of higher-order effects at the lower incident energy used, as suggested in Ref. [21]. We also note that the second bump observed in Zinser *et al.* is not seen in the spectrum with experimental significance.

In Fig. 3, the present $B(E1)$ distribution is also compared with a calculation using the three-body model description of Esbensen and Bertsch [20], where the energy resolution (1σ) of $\Delta E = 0.17\sqrt{E_{rel}}$ MeV in $d\sigma/dE_{rel}$ is taken into consideration. The model, which includes the two-neutron correlations in the initial and final states, is shown to reproduce the data very well without normalization adjustment. The agreement of both the spectral shape and absolute strength indicates the presence of a strong two-neutron correlation in ^{11}Li.

The spatial two-neutron correlation in the ground state of two-neutron halo nuclei can be further examined by applying the non-energy-weighted $E1$ cluster sum rule [20,26], described by

$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2\langle r_1^2 + r_2^2 + 2\boldsymbol{r_1}\cdot\boldsymbol{r_2}\rangle = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2\langle r_{c,2n}^2\rangle, \tag{2}$$

where $\boldsymbol{r_1}$, $\boldsymbol{r_2}$ are the position vectors of the two valence neutrons relative to the core, and $r_{c,2n}$ is the distance between the core and the center-of-mass of the two halo neutrons. The term $\boldsymbol{r_1}\cdot\boldsymbol{r_2}$ involves the opening angle θ_{12} of the two valence neutrons seen from the core. The value of $r_{c,2n}$, and hence $B(E1)$, becomes larger for the smaller separation of the two neutrons, when the angle θ_{12} approaches 0°. Thus, the value of θ_{12} provides a good measure of the two-neutron spatial correlation.

The integral of the $E1$-response calculation (solid curve) for $0 \leq E_{\rm rel} \leq 3$ MeV accounts for 80% of the total $E1$ cluster sum-rule strength above the neutron decay threshold. When we assume this relative strength, the observed $B(E1)$ strength, 1.42 ± 0.18 e^2 fm^2 up to $E_{\rm rel} = 3$ MeV, is translated into 1.78 ± 0.22 e^2 fm^2 for $E_{\rm x} \geq S_{\rm 2n}$ (the uncertainty indicated is only the experimental one). With this strength, one can extract the value of $\sqrt{\langle r_{c,2n}^2\rangle} = 5.01 \pm 0.32$ fm. Taking the sum-rule value 1.07 e^2 fm^2 for two noncorrelated neutrons, predicted in Ref. [20], the current value 1.78 ± 0.22 e^2 fm^2 results in $\langle\theta_{12}\rangle = 48^{+14}_{-18}$ degrees. This angle is significantly smaller than the average opening angle of 90° expected for two noncorrelated neutrons. Thus, an appreciable two-neutron spatial correlation is implied for the halo neutrons.

Besides this theory, there exist a large number of theoretical calculations [22–30] dealing with the Coulomb dissociation of ^{11}Li. Our new result, in combination with these theoretical studies, should provide fruitful information on the crucial properties of this intriguing Borromean system. For instance, we note that the theory adopted here still deviates from the measured strength distribution below $E_{\rm rel} = 0.3$ MeV and in its peak position, which will warrant further theoretical study. Such comparisons are left for future work since parameters employed in the earlier theoretical calculations were often adjusted, in some degree, to the earlier experimental results.

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