Coulomb Breakup of $^{11}$Li

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Abstract. A new kinematically complete measurement of the Coulomb breakup of two-neutron halo nucleus $^{11}$Li on a Pb target has revealed a strong soft-E1 transition strength peaking at $E_x \sim 0.6$ MeV. This soft E1 strength amounts to $1.42 \pm 0.18$ e$^2$fm$^2$, corresponding to $4.5 \pm 0.6$ Weisskopf units (W.u.). The observed $B(E1)$ distribution has been found in excellent agreement with a three-body calculation with strong two-neutron correlation and final state interactions.

Soft E1 excitation is a unique property of halo nuclei, where low-energy E1 strength is strongly enhanced compared to that for ordinary nuclei. For instance, the Coulomb breakup of the one-neutron halo nucleus $^{11}$Be showed strong E1 transitions that peaks at $E_x \sim 0.8$ MeV [1, 2]. In this case, the soft E1 excitation is understood by the direct breakup mechanism, where the halo nucleus breaks up directly without forming any resonances. In this mechanism, the large $B(E1)$ strength can be interpreted as an amplified image of the large amplitude of the halo radial wave function. The selectivity to the s-wave halo component of the ground state of this reaction mechanism is thus used to extract the spectroscopic factor for the halo configuration [1, 2, 3].

On the other hand, the nature of E1 response of two-neutron halo nuclei, such as $^{11}$Li is still not known. This is due mainly to the controversial situation on the three previous experiments on the soft E1 excitation by the Coulomb dissociation of $^{11}$Li [4, 5, 6]. In fact these three experimental results are inconsistent among each other as shown in Fig. 1. This discrepancy may be attributed to the difficulties in detecting two neutrons unambiguously. Theoretically, reaction mechanisms suffer from the complexity which may arise from the two-neutron halo correlations. We have thus studied this case with much more statistics and with careful two-neutron detection.

The experiment was performed at the radioactive beam facility RIPS at RIKEN. The $^{11}$Li ions bombarded the Pb target with thickness of 346 mg/cm$^2$ at an average energy of 69.7 MeV/nucleon. The point of this experiment is that we could measure the two neutrons up to $E_{rel} \sim 0$ MeV by using the causality analysis with the two separate neutron-detector walls. The details of the experiment and this technique of exclusion of cross-talk events are described in Ref. [7].

In Fig.1 the deduced $B(E1)$ distribution of $^{11}$Li is shown by solid circles as a function of the relative energy of $^9$Li+n+n. The current result shows a strong peak at $E_{rel} \sim 300$ keV ($E_x=E_{rel}+S_{2n} \sim 600$ keV), which is in sharp contrast to those from the previous three experiments that peaked at $E_{rel}=600$–1000 keV. This substantial difference may be due to the insensitivity at low relative energies in the previous three experiments as discussed in Ref. [7]. As is also shown in Fig. 1, the current $B(E1)$ spectrum is in good agreement with a theoretical
three-body calculation (solid curve) [8], where strong two-neutron correlation and final state interactions are taken into account.

**Figure 1.** The $B(E1)$ distribution of $^{11}$Li obtained in the current Coulomb breakup experiment (solid circles). The present data points are compared with the previous ones observed at 28 MeV/nucleon at MSU (dotted-dashed line) [4], at 43 MeV/nucleon at RIKEN (solid histogram) [5], and at 280 MeV/nucleon at GSI (zone between dashed-lines) [6]. The present result is also compared with the three-body calculation shown by the solid curve. Reprinted figure with permission from [7]. Copyright (2006) by the American Physical Society.

One can also examine such neutron-neutron correlation in the ground state of $^{11}$Li by using the non-energy weighted E1 cluster sum rule written by,

$$B(E1) = \int_{-\infty}^{+\infty} \frac{dB(E1)}{dE_{rel}} dE_{rel} = \frac{3}{4\pi} \left( \frac{Ze}{A} \right)^2 \langle r_1^2 + r_2^2 + 2r_1 \cdot r_2 \rangle,$$

where $r_1, r_2$ are the coordinates of two valence neutrons relative to the core. The term $r_1 \cdot r_2$ contains the opening angle $\theta_{12}$ of two valence neutrons, which is a measure of the two-neutron correlation. The integrated $B(E1)$ strength obtained in the current experiment is $1.42\pm0.18$ $e^2$ fm$^2$ (4.5±0.6 Weisskopf units) for $0 \leq E_{rel} \leq 3$ MeV. According to the theory, this value can be extrapolated to the cluster sum of $1.78\pm0.22$ $e^2$ fm$^2$, which corresponds to the mean opening angle of $\langle \theta_{12} \rangle = 48^{+14}_{-18}$ degrees. This value is smaller than that for the model with independently-moving two neutrons in the halo, i.e., $\langle \theta_{12} \rangle = 90$ degrees. More detailed analysis on two neutron correlation as well as n-$^9$Li correlation is now in progress for further clarification of the nature of the two-neutron halo nucleus.

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