Three-body correlation in $^{11}$Li studied via low-lying E1 excitation

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Abstract. We have studied the structure of the Borromean nucleus $^{11}$Li via the Coulomb breakup with a Pb target at 70 MeV/nucleon. Momentum vectors of the breakup particles, $^9$Li and two neutrons, were measured in coincidence to reconstruct the $B$(E1) energy spectrum. The strong E1 transitions were observed at $E_{\text{rel}} \sim 0.3$ MeV with the $B$(E1) = 1.42(18) e$^2$fm$^2$ (=4.5(6)W.u.), which is the largest E1 strength ever observed in such low excitation energies. This result gives an evidence that the two valence neutrons have spatial dineutron-like correlation. The correlation of the two neutrons is supported by the non-energy weighted E1 cluster sum rule which provides the mean opening angle of $\langle \theta_{12} \rangle = 48^{+18}_{-18}$ degrees for the two valence neutrons relative to the center of the core. It is suggested that this narrow angle can be related to the angular momentum mixing in the halo neutrons of $^{11}$Li.

1. Introduction

Pairing correlation is one of the key properties of nuclear structure. Classical pairing correlation in nuclei can be described as a Cooper pair in the framework of the BCS theory, where two like nucleons are orbiting in the opposite directions with a weak coupling. On the other hand, BEC-type strong coupling in two neutrons has recently been discussed [1, 2], where a dineutron-like structure with strong spatial correlation is formed at very low-dense nuclear environment. In this sense, it is of great importance to investigate two neutron correlations in halo nuclei such as $^{11}$Li, where two halo neutrons form a low-dense nuclear matter surrounding the core of $^9$Li. Here, we present the recent experimental results of Coulomb breakup of $^{11}$Li and discuss the extracted two neutron correlation from the observed E1 response.

Low-lying electric dipole excitation, so called “soft dipole excitation”, is one of the unique properties of halo nuclei. As is shown for the E1 response of the one-neutron halo nuclei such as $^{11}$Be [3, 4, 5] and $^{19}$C [6], substantial enhancement of E1 strengths of the order of 1 W.u. has been found to be concentrated at low excitation energies of about 1 MeV. For one-neutron halo nucleus, this enhancement has been understood well by the direct breakup mechanism. In this case the E1 strength distribution is expressed as a Fourier-Bessel transform of the spatial wave function, and thus the low-energy part of the E1 distribution reflects the large amplitude of the spatial density distribution. This fact can be seen from a viewpoint of non-energy weighted E1 cluster sum rule [14], which is written as,

$$B(\text{E1}) = \int_{-\infty}^{\infty} \frac{dB(\text{E1})}{dE_x} dE_x = \frac{3}{4\pi} \left( \frac{Ze}{A} \right)^2 \langle r^2 \rangle,$$

(1)
where $r$ represents the distance between the halo neutron against the core. Namely, this equation shows that the low-lying E1 strength is proportional to the r.m.s. distance of the halo neutron. For the case of $^{11}$Be, the $\sqrt{\langle r^2 \rangle}=5.77 \pm 0.16 \text{ fm}$ was extracted\cite{5}, which represents indeed a large distance of the halo neutron from the core.

E1 response of the two-neutron halo nuclei such as $^{11}$Li is considered to be more complicated. In addition to the direct breakup mechanism, two-neutron correlation is considered to contribute to the soft E1 excitation. This can be seen from the non-energy weighted E1 cluster sum rule for the two neutron halo written as,

$$B(E1) = \int_{-\infty}^{+\infty} dB(E1) dE_x$$

$$= \frac{3}{4\pi} \left( \frac{Ze}{A} \right)^2 \langle r_1^2 + r_2^2 + 2r_1 \cdot r_2 \rangle$$

$$= \frac{3}{\pi} \left( \frac{Ze}{A} \right)^2 \langle r_{2n-c}^2 \rangle,$$

where $r_1$ and $r_2$ represent position vectors of two halo neutrons relative to the center of the core. $r_{2n-c}$ denotes the distance between the core and the center of mass of the two valence neutrons. The term $r_1 \cdot r_2$ contains the opening angle $\theta_{12}$ of the two valence neutrons, which is a measure of the two-neutron correlation. This equation indicates that not only the amplitude of the spatial distribution of each halo neutron, but also the spatial correlation, ($r_1 \cdot r_2$), contributes to the enhancement of the $B(E1)$ amplitude. It is thus important to determine the low-lying E1 distribution of two-neutron halo nuclei. Although $^{11}$Li is the most investigated two-neutron halo nucleus, the $B(E1)$ strength was only poorly known. This situation is attributed to controversial previous Coulomb breakup data taken from MSU\cite{7}, RIKEN\cite{8} and GSI\cite{9} in the 90's. Hence, we have done an improved measurement of the soft E1 strength distribution with higher statistics and less ambiguity caused by cross-talk events in detecting two neutrons in order to clarify the cluster correlations in $^{11}$Li.

2. Experiment

The E1 response of $^{11}$Li has been extracted from the full exclusive Coulomb breakup experiment of $^{11}$Li on a Pb target at an incident energy of approximately 70 MeV/nucleon at RIKEN. A secondary beam of $^{11}$Li was produced by fragmentation of a 100 MeV/nucleon primary $^{18}$O beam in a thick Be production target and separated using the RIPS radioactive beam line\cite{11}. The $^{11}$Li beam bombarded the Pb target of thickness 346 mg/cm\(^2\) with an average energy of 70 MeV/nucleon. The momentum of the beam ion was obtained by tracing the trajectory with two PPACs and by measuring the time of flight (TOF) using a thin plastic scintillator relative to an RF signal of the Cyclotron.

The outgoing particles, a $^9$Li ion and two neutrons, were emitted in a narrow kinematical cone at forward angles. The $^9$Li ion was bent by a large-gap dipole magnet, tracked with a drift chamber, and then traversed through a hodoscope. The momentum of the $^9$Li ion was thus obtained using the tracking information in combination with the TOF.

The momenta of neutrons were obtained using the TOF and position information at the neutron detector arrays, which were composed of 54 rods of plastic scintillators arranged into two layers. Two layer arrangement is used to disentangle the cross talk events by use of the causality analysis. The momentum vectors of outgoing three particles were then combined to extract the invariant mass of the excited $^{11}$Li nuclei. The details of the experiment and this technique of exclusion of cross-talk events are described in Ref.\cite{10}.
Figure 1. Electric dipole strengths of $^{11}$Li obtained in the present Coulomb breakup experiment (solid circles). a) The data are compared with the previous three results in the 90’s, obtained at MSU (solid curve) [7], at RIKEN (solid histogram) [8], and at GSI (dashed zones) [9]. b) The data are compared with the three-body theories by H. Esbensen and G.F. Bertsch [14]. The solid curve shows the calculation for the full $nn$ correlation, the dotted curve shows the calculation including $nn$ correlation but without final state interactions, the dashed curve shows the calculation for no correlation.

3. Results and discussions

Figure 1(a) shows the $B(E1)$ distribution obtained in the present experiment, compared with the previous three experiments [7, 8, 9]. A strong peak at $E_{\text{rel}} \sim 300$ keV ($E_x = E_{\text{rel}} + S_{2n} \sim 600$ keV) is observed, which is in sharp contrast to those from the previous three experiments that peaked at $E_{\text{rel}} = 600$–1000 keV. This difference can be attributed to the insensitivity at low relative energies in the previous experiments as discussed in Ref. [10]. As is compared in Fig. 1(b), the current $B(E1)$ spectrum agrees well with a theoretical three-body calculation (solid curve) [14], where the two-neutron correlation and final state interactions are taken into account fully. On the other hand, the calculation without $nn$ correlation and/or final state interactions could not reproduce the data.

Such neutron-neutron correlation in the ground state of $^{11}$Li can be examined by using the non-energy weighted E1 cluster sum rule as in Eq. (4). The integrated $B(E1)$ strength obtained in the current experiment is $1.42 \pm 0.18$ e$^2$fm$^2$ (4.5$\pm$0.6 Weisskopf units) for $0 \leq E_{\text{rel}} \leq 3$ MeV. According to the theory, this value can be extrapolated to the cluster sum of $1.78 \pm 0.22$ e$^2$fm$^2$, which corresponds to the mean opening angle of $\langle \theta_{12} \rangle = 48^{+14}_{-16}$ 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.

The narrow opening angle can be related to the mixture of different angular momentum in
the halo neutrons of $^{11}$Li. The mixture of s-wave and p-wave neutrons in the $^{11}$Li halo was suggested from the knockout reaction of $^{11}$Li [12] and the $\beta$ decay study [13]. We assume thus that the $^{11}$Li ground state wave function has the following form as in,

$$\Psi(^{11}\text{Li}) = \Psi(9\text{Li}) \otimes \left(\alpha|1s\rangle^2 + \beta|0p\rangle^2\right),$$

(5)

where $\alpha$ and $\beta$ respectively denote the amplitude of s-wave and p-wave components of two halo neutrons. In this case, the expectation value $\langle \cos \theta_{12} \rangle$ can be written as,

$$\langle \cos \theta_{12} \rangle = \frac{\alpha^2 \langle |1s\rangle^2 | \cos \theta_{12} | |1s\rangle \rangle + \beta^2 \langle |0p\rangle^2 | \cos \theta_{12} | |0p\rangle \rangle + 2\alpha\beta \langle |0p\rangle^2 | \cos \theta_{12} | |1s\rangle \rangle}{2\alpha^2 \langle |1s\rangle^2 \rangle + \beta^2 \langle |0p\rangle^2 \rangle + 2\alpha\beta \langle |0p\rangle^2 | \cos \theta_{12} | |1s\rangle \rangle}$$

(6)

Namely, only the cross term with different initial and final states can remain in the integration for $\cos \theta_{12}$. Hence, it turns out that the wave function with no mixture in different parity states in the two neutron halos leads this expectation value to vanish, thereby resulting in $\langle \cos \theta_{12} \rangle=0$ degrees. The observation of significantly narrower angle than 90 degrees directly shows that the mixture of different parities in the halo neutrons should indeed be revealed. When we assume the maximum overlap between the wave function of $|1s\rangle^2$ and $|0p\rangle^2$ in radial wave function, then $\alpha$ becomes equal to $\beta(=1/\sqrt{2})$. This leads to the following expectation values,

$$\langle \cos \theta_{12} \rangle = 1/\sqrt{3} \quad \langle \theta_{12} \rangle = 54.7\degree,$$

(7)

which is rather close to the current experimental observation.

For the more quantitative argument, we need more sophisticated theories. For instance, Myo et al. have recently calculated the $^{11}$Li wave function including tensor correlations [15], and have deduced the $B(E1)$ distribution. It is interesting to note that their calculation shows the di-neutron correlation with $\theta_{12}$ to be about 20 degrees on top of the less correlated neutrons with about 90-100 degrees. The two neutron correlation extracted from the current $B(E1)$ distribution is also discussed in other theoretical works as well [16, 17, 18].

4. Summary and outlook

In summary we have observed strong E1 transitions peaking around $E_{rel} \sim 0.3$ MeV ($E_{x} \sim 0.6$ MeV) in the energy spectrum in the $^{11}$Li breakup on the Pb target at 70 MeV/nucleon. The E1 strength up to $E_{rel}$=3 MeV amounts to as large as $B(E1)=1.42(18) \ e^2f$m$^2$. The spectrum was compared with a three-body model with/without n-n correlation, where an excellent agreement with data was obtained when the n-n correlation in the ground state and final state interactions are both incorporated. The non-energy weighted E1 cluster sum rule supported the spatial correlation of two valence neutrons in the ground state, where the integrated $B(E1)$ is consistent with the model with the opening angle of about 50 degrees. This narrow opening angle is also found related to the mixture of different parities in $^{11}$Li. The mixture of higher angular momentum may be related to the stronger spatial correlation in low-density nuclear matter, as is discussed in Ref. [1, 2]. More detailed analysis on two neutron correlation as well as n-9Li correlation is now in progress for further clarification of the nature of the two-neutron halo nucleus.

To further investigate these phenomena at the new-generation RI beam factory in RIKEN, we will construct the large-gap superconducting spectrometer SAMURAI (Superconducting Analyser for Multi-particles from Radio-isotope Beam), as well as the neutron detectors with large efficiencies NEBULA (NEutron Detection System for Breakup of Unstable Nuclei with Large Acceptance). The bending power of the superconducting magnet should reach about 7 T·m, which can bend $A/Z=3$ particle by about 60 degrees. It is expected that the construction will be completed by 2010. In this new facility, not only the two-neutron halo system, but four-neutron halo/skin system will also be investigated to reveal more exotic cluster correlations.
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