論文の内容の要旨

論文題目　Neutron-neutron correlation in Borromean nucleus ^{11}Li via the (p, pn) reaction
（(p, pn) 反応を通じたボロミアン核における中性子相関の研究）

氏名　久保田　悠樹

1 Introduction

Neutron-neutron correlation in light neutron-rich Borromean nuclei has attracted much attention. These nuclei are weakly bound and have a surface made of neutrons. In such a weakly-bound system, a hypothetical bound state of two neutrons, *dineutron*, may exist near the surface. It has long been presumed that the neutron-neutron correlation caused by the dineutron (dineutron correlation) is a key ingredient to understand the binding mechanism as well as the exotic structures of these nuclei.

The dineutron correlation was first discussed by Migdal by solving the three-body problem. He showed that under certain circumstances there appears a bound state of the two particles, even in the case when the attraction between the two particles is too weak to form a bound state outside the potential. The loosely-bound nuclei located at the neutron drip line such as ^{11}Li are considered to be the best environments to realize such a condition.

There have been extensive studies to search for dineutron correlation in ^{11}Li. From an experimental point of view, most studies supported the existence of the dineutron correlation in ^{11}Li. However, no studies could provide the spatial distribution of two neutrons in ^{11}Li. Moreover, the obtained opening angle, the measure of the dineutron correlation, was not consistent between different studies.

2 Quasi-free (p, pn) reaction followed by the neutron emission

The neutron-neutron correlation can be fully investigated by determining the spatial distributions of two valence neutrons in the ground state. However, it is experimentally difficult to measure the positions of two neutrons in the ground state at the same time because the final-state interactions

(FSIs) take place in the decay process. In this thesis, we approached the spatial distributions of two valence neutrons in ^{11}Li by dividing the problem into two:

- Measurement of the one-neutron ground-state momentum and
- Spectroscopy of the ^{9}Li + n subsystem.

The one-neutron momentum distribution provides the most direct information on the spatial distribution of the valence neutron of ^{11}Li. On the other hand, the structure of the ^{9}Li + n subsystem gives information on the interaction between a ^{9}Li nucleus and a neutron, which is essential to describe the ^{9}Li + n + n system. By combining all the information (kinematically complete measurement), the spatial distribution of two neutrons are reconstructed as an opening angle distribution without losing the correlation information among them.

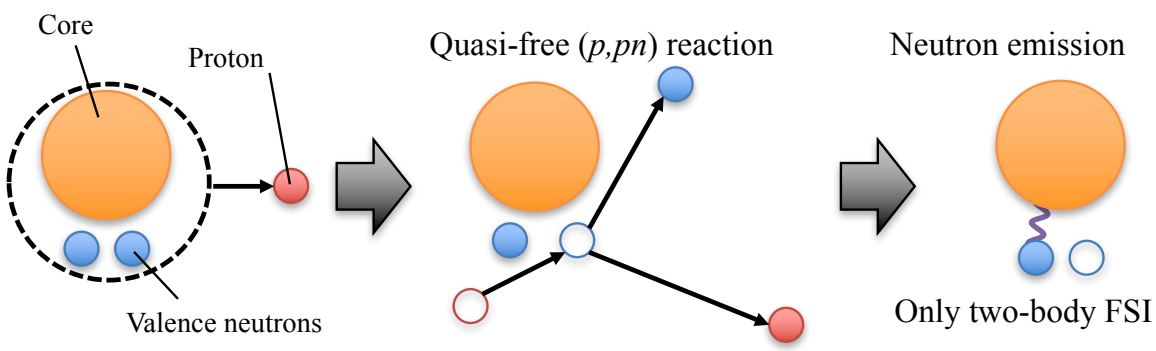

Figure 1: Conceptual diagram of the quasi-free (p, pn) reaction followed by the neutron emission.

The quasi-free (p, pn) reaction was employed to realize the measurement described above. A conceptual diagram of the reaction is shown in Fig. 1. One of the valence neutrons is knocked out by the probe proton. Thanks to the quasi-free scattering picture, the motion between the knocked-out neutron and the residual can be well separated from that in the residual nucleus, and thus the reaction is hardly affected by the three-body FSI. After the occurrence of the quasi-free (p, pn) reaction, the reaction residue immediately decays due to the Borromean nature. Therefore, it is possible to measure momentum vectors of all the constituents at the same time. It should be noted that the quasi-free (p, pn) reaction is transparent so that one can probe the whole volume of the nucleus.

3 Experiment

The experiment was performed at Radioactive Isotope Beam Factory (RIBF) in RIKEN by using the SAMURAI spectrometer. This measurement required high luminosity to have as much statistics as possible. For this purpose, very thick liquid hydrogen target MINOS was used with a high intense ^{11}Li secondary beam. The secondary beam was produced through

the projectile fragmentation reaction from the ^{48}Ca primary beam at 345 MeV/nucleon with an intensity of 400 pnA bombarding on a primary target of ^{9}Be. The secondary beam was purified through the BigRIPS fragment separator. The averaged beam intensity was 10^5 pps with a purity of 70%. The secondary beam was transported to the location of the secondary target in the experimental room by employing the newly-developed beam optics.

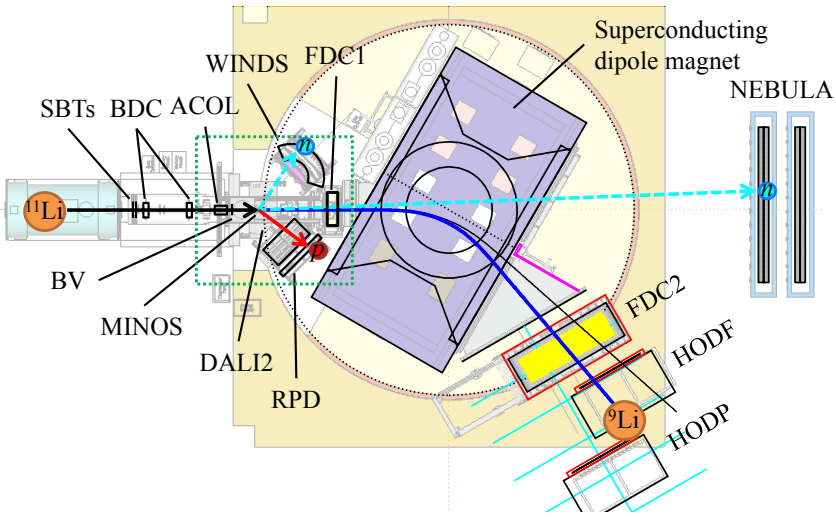

Figure 2: Top view of the experimental room view.

The key component of this experiment is the setup to obtain the kinematically complete information on the ^{11}Li(p, pn) reaction. Figure 2 shows a top view of the experimental setup. The incident ^{11}Li beam bombarded on a liquid hydrogen target of the MINOS, and then, the ^{11}Li$(p, pn)^{10}$Li$^* \rightarrow {}^{9}$Li$+n$ reaction took place. In order to reconstruct the momentum vectors of two valence neutrons, all of the relevant momentum vectors, i.e. those of the ^{11}Li beam (detected by beam line detectors), the recoil proton (by RPD), the knocked-out neutron (by WINDS), the heavy fragment ^{9}Li (by SAMURAI spectrometer), the decay neutron (by NEBULA), and the gamma ray emitted from the heavy fragment ^{9}Li (by DALI2) were determined event by event and kinematically complete measurement was realized.

4 Results and discussion

The spectroscopy of the reaction residue ^{10}Li provided strong constraints on the interaction between a neutron and a ^{9}Li nucleus, which is essential to describe ^{11}Li. The existence of the s-wave virtual state and of the p-wave resonance state was confirmed in the invariant mass spectrum of the ^{10}Li, and their resonance parameters were determined. Moreover, the d-wave resonance state was newly found at $E_r = 5.52 \pm 0.04$ MeV with a decay width of $\Gamma = 0.72 \pm 0.10$ MeV. This new resonance state has not been reproduced by available theoretical models.

The one-neutron ground-state momentum distribution gave the information of the spatial distribution of the valence neutron. The multipole decomposition analysis (MDA) was performed

on the internal momentum of the knocked-out neutron k_Y. The fraction of each multipole up to d-wave was obtained as $35 \pm 4\%$, $59 \pm 1\%$, and $6 \pm 4\%$ for the two-neutron configurations $(s_{1/2})^2$, $(p_{1/2})^2$, and $(d_{5/2})^2$ or $(d_{3/2})^2$, respectively. The fraction of the s-wave is small compared to the previous works. This indicates the dineutron correlation in ^{11}Li can be weaker than previously reported.

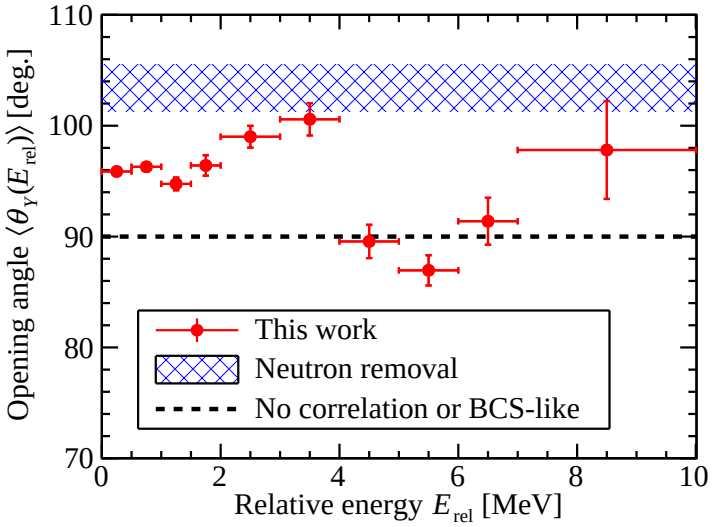

Figure 3: Expectation values of the opening angle in momentum space $\langle\theta_Y(E_{\rm rel})\rangle$ as a function of the relative energy $E_{\rm rel}$ of ^{10}Li.

The spatial distribution of two valence neutrons in ^{11}Li was studied by using the relative energy as a measure of the radial position. The relative energy dependence of the opening angle distribution of two neutrons was measured for the first time, as shown in Fig. 3. The result suggested that the dineutron correlation developed in the surface region. The averaged expectation value of the opening angle between the two neutrons was determined as $\langle\theta_Y^x\rangle$ = 85 ± 10 degrees. The larger opening angle as compared with the previous work implies the weaker dineutron correlation in ^{11}Li than expected from the previous works.

5 Conclusion

In the present work, the neutron momentum distribution in ^{11}Li was determined by employing the quasi-free (p, pn) reaction. We employed a new method of kinematically complete measurement, which enabled us to extract the ground-state neutron-neutron correlation as well as to investigate the structure of the ^{9}Li+n subsystem through the momentum measurement and the invariant mass spectroscopy, respectively. The d-wave resonance state was newly found in the invariant mass spectrum of ^{10}Li. The fraction of each multipole was determined from the one-neutron ground-state momentum distribution by employing the MDA. The obtained opening angle distribution indicates the dineutron correlation in ^{11}Li can be weaker than previously reported.