Study of spin-isospin response of ^{11}Li neutron-drip-line nucleus with PANDORA

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Abstract. The spin-isospin responses of the ^{11}Li drip-line nucleus has been measured. Preliminary results of the $^{11}\text{Li}(p,n)^{11}$Be experiment in inverse kinematics at RI Beam Factory (RIBF) of RIKEN Nishina Center are presented including the observation of $1n$, $2n$, t, d, 2α and ^{6}He+α decay channels of ^{11}Be reaction product. Details of the experimental setup based on PANDORA (Particle Analyzer Neutron Detector Of Real-time Acquisition) low-energy neutron detector and the SAMURAI large-acceptance magnetic spectrometer are described.

1. Introduction

The studies of dynamic properties of exotic nuclei, such as giant resonances, which manifest themselves at higher excitation energies (>10–15 MeV) are of much current interest worldwide. Until recently, only the spin-isospin collectivity in stable isotopes was investigated [1]. There are no available data on spin-isospin collectivity for nuclei with large isospin asymmetry factors, where $(N - Z)/A$ >0.25. We investigated the ^{11}Li nucleus in this unexplored region. At the RIKEN Radioactive Isotope Beam Factory (RIBF), the GT transitions including the GT resonance from the ^{11}Li drip line nucleus were measured at 200 MeV/nucleon beam energies. The (p, n) reactions in inverse kinematics are efficient tools to extract the B(GT) strengths of unstable isotopes [2, 3].

The charge-exchange (p, n) reactions at intermediate beam energies (E/A >100 MeV) and small scattering angles can excite Gamow-Teller (GT) states up to high excitation energies in the final nucleus, without Q-value limitation [4]. The combined setup of PANDORA (Particle Analyzer Neutron Detector Of Real-time Acquisition) low-energy neutron counter and the SAMURAI magnetic spectrometer [5] together with a thick liquid hydrogen target allows us to perform such measurements with high luminosity [6]. In this setup, the neutron detector is used for the detection of the recoil neutrons. The neutron kinetic energies are deduced by the time-of-flight (ToF) technique and SAMURAI is used for tagging the decay channel of the reaction residues. Many relevant decay channels after the charge-exchange reaction can be measured in a single magnetic rigidity setting owing to the large acceptance of the SAMURAI spectrometer. Such a method was already successfully used in our first (p, n) experiment on ^{132}Sn [7]. It was proven that we can take data on unstable nuclei with quality comparable to those on stable nuclei.

Random gamma background, which mainly arises from the experimental environment, cannot be distinguished from the neutrons by ToF information alone. In order to eliminate background events due to gamma rays, we developed the PANDORA system [8, 9] extracting an additional parameter, the pulse-shape discrimination (PSD). PANDORA consists of EJ-276 plastic scintillator bars [10], which are sensitive to the difference between neutrons and gamma rays [11], and are coupled to a photomultiplier tube (PMT) [12] at each end.

2. Experimental setup and conditions

The experiment was performed at the RI Beam Factory (RIBF) of RIKEN Nishina Center. A secondary cocktail beam of unstable ^{11}Li and ^{14}Be was produced via the fragmentation reaction of a 230 MeV/u ^{18}O primary beam on a 14-mm-thick ^{9}Be target installed at the F0 focal plane of the BigRIPS separator [13]. Two degraders were installed at F1 and F5 with thicknesses of 5-mm and 2-mm, respectively. In order to reduce the beam contamination by tritons (as their production rate is much higher than those of nuclei of interest), a special collimator was installed in the beam line.

Figure 1 shows a schematic view of the experimental setup around the SAMURAI spectrometer. Downstream of STQ25, two 1-mm-thick plastic scintillators (SBT1,2) were installed for the detection of beam particles. The SBTs were used to produce the beam trigger (threshold was set to Z >2). The particle identification (PID) for the incident beam was performed on an event-by-event basis by measuring the energy loss in SBTs and the ToF of the beam particles between the plastic scintillation counters installed at F7 and SBTs. The a) panel of Fig. 2 shows the result of the beam PID. We eliminated the multi-hit event using the multi-hit TDC information recorded at the start-timing counter. Downstream from the SBTs, two multi-wire drift chambers were installed (BDC1,2) for measuring the trajectories of the beam particles. The secondary cocktail beam consisted of ^{11}Li at 182 MeV/u with intensity of 2.5×10^5 particle/s and ^{14}Be at 198 MeV/u with intensity of 1×10^5 particle/s with purities of 48% and 19%, respectively. The triton contamination was below 30%. The secondary beam was

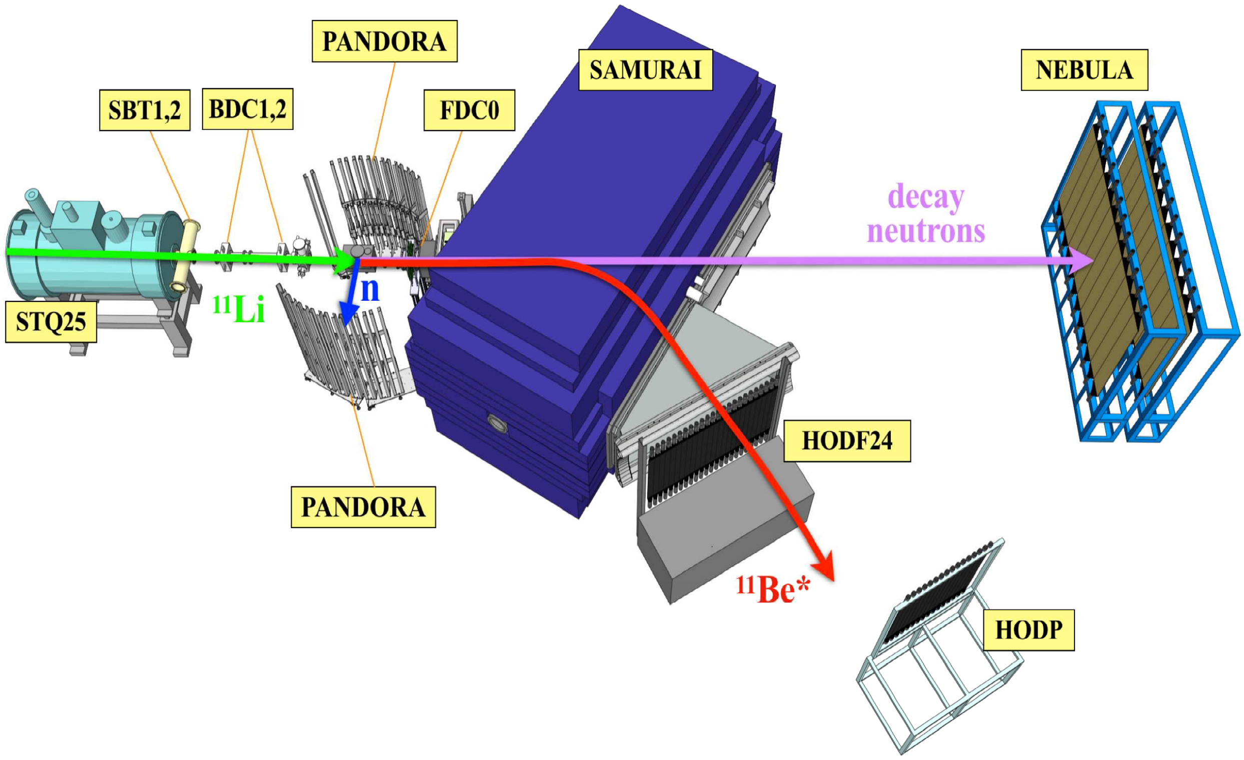

Figure 1. A schematic view of the experimental setup.

transported onto a 10-mm-thick, 60-mm diameter liquid hydrogen (LH) target (rotated by 45°) at the secondary target position of SAMURAI (F13).

The reaction residues entered into SAMURAI after passing through the forward drift chamber, FDC0. The magnetic field of the spectrometer was set to 2.75 T. The PID of the beam residue produced in the target was performed in the SAMURAI spectrometer based on the ToF–ΔE method. The ToF was measured by using the plastic scintillators SBT1,2 and HODF24 (a wall of 24 plastic scintillator bars with dimensions of $1200^W \times 100^H \times 10^D$ mm^3) with a flight-path length of around 10 m. The energy loss ΔE was measured by HODF24. Those two bars of HODF24, which were hit by the unreacted secondary beam, were excluded from the trigger. Panel b) of Fig. 2 shows a typical PID spectrum detected in HODF24 for the reaction products produced from the ^{11}Li beam bombarding the filled liquid-hydrogen target. The thickness of the filled target cell was obtained by laser displacement meter and the effective target thickness along the beam direction through analysis of the profile data. The profile analysis provided the thickness of the target central region, after 45-degree rotation, as 15.8 mm. The reaction products and decay particles can be clearly identified. Further downstream, an additional wall (HODP device) with 16 plastic bars (same as HODF24 bars) was installed. NEBULA was used to detect the fast decay neutrons of the reaction products (decays by $1n$ and $2n$ emissions).

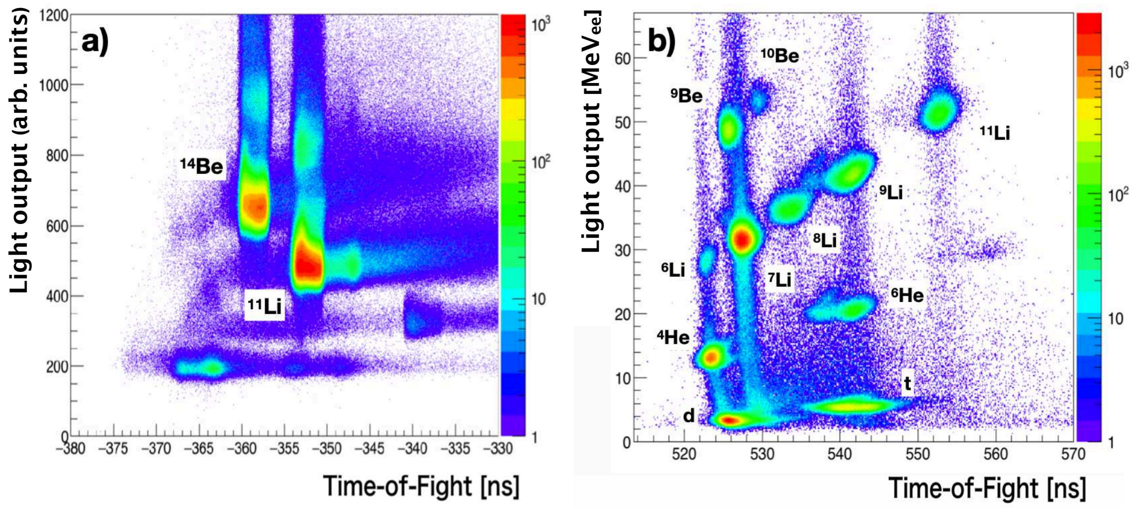

Figure 2. The incoming beam PID spectrum (a) determined with the SBT detectors and the PID (b) of the reaction residues detected in HODF24 of the reaction products produced from the ^{11}Li beam bombarding the filled liquid-hydrogen target.

3. Neutron-gamma separation with PANDORA

The neutron detector setup on the left and right sides of the LH target consisted of 27 PANDORA plastic scintillators and 13 additional scintillator bars of WINDS. The distance between the LH target and PANDORA or WINDS was around 125 cm. Each detector was placed such that the 25-mm-wide (PANDORA) or 30-mm-wide (WINDS) plane faced the target. The left and right wings with respect to the beam line covered the laboratory recoil angular region of 47°–113° and 62°–134°, respectively, with 3.25° steps. PANDORA was optimized to detect neutrons with a kinetic energy of 0.1–5 MeV. The time reference for the ToF was taken from SBT1,2. The threshold for the light output in the scintillator was set to be 60 keV$_{ee}$, corresponding to 200 keV proton energy.

All bars had duplicated readout: CAEN V1730 modules were used for charge and PSD information while an analog circuit was used for timing and triggering. For the digital data-acquisition system (DDAQ) we daisy chained seven CAEN V1730 waveform digitizers using an optical connection. DDAQ applied a consumer-configured trigger condition. The standard SAMURAI detectors (beam-line detectors, hodoscopes and NEBULA) employed analog readout with analog triggering (DAQ). The acquisition in the digitizers was not based on the self-triggering of each channel. The local triggering option of the two-two coupled channels was used to ensure the coincidence between the top and bottom PMTs of PANDORA. The validation of the local triggers came from an external trigger based on the programmed software criteria. The validation signal originated from the triple coincidence of “BEAM“ (from SBT detectors) and analog “PANDORA“ (recoil neutron) and “HODOSCOPE“ (reaction residues at hodoscopes). The typical trigger rate was 1.3×10^3 Hz.

Figure 3 shows the two-dimensional plot of PSD$_{mean}$ vs. total light output of a PANDORA bar for events associated with ^{11}Li beam. Clear separation of neutron-like events is observed. To evaluate the PSD performance of PANDORA, the Figure-of-Merit (FoM) based on the window method [8] was used. The inset panel of Fig. 3 presents an example for the projected PSD$_{mean}$ distributions of neutron- and gamma-like events, with 200-keV$_{ee}$ wide window centered at light outputs of 500 keV$_{ee}$; the FoM value is 1.22 ± 0.01.

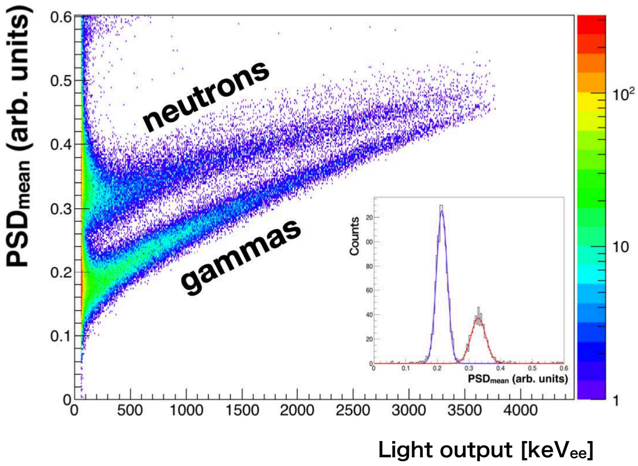

Figure 3. The PSD$_{mean}$ vs. light output spectrum of PANDORA shows the importance of separating neutrons and random gamma background. The inset panel presents the projected PSD$_{mean}$ distributions of neutron- and gamma-like events, with 200-keV$_{ee}$ wide window centered at 500 keV$_{ee}$ light output. The corresponding FoM value is 1.22±0.01.

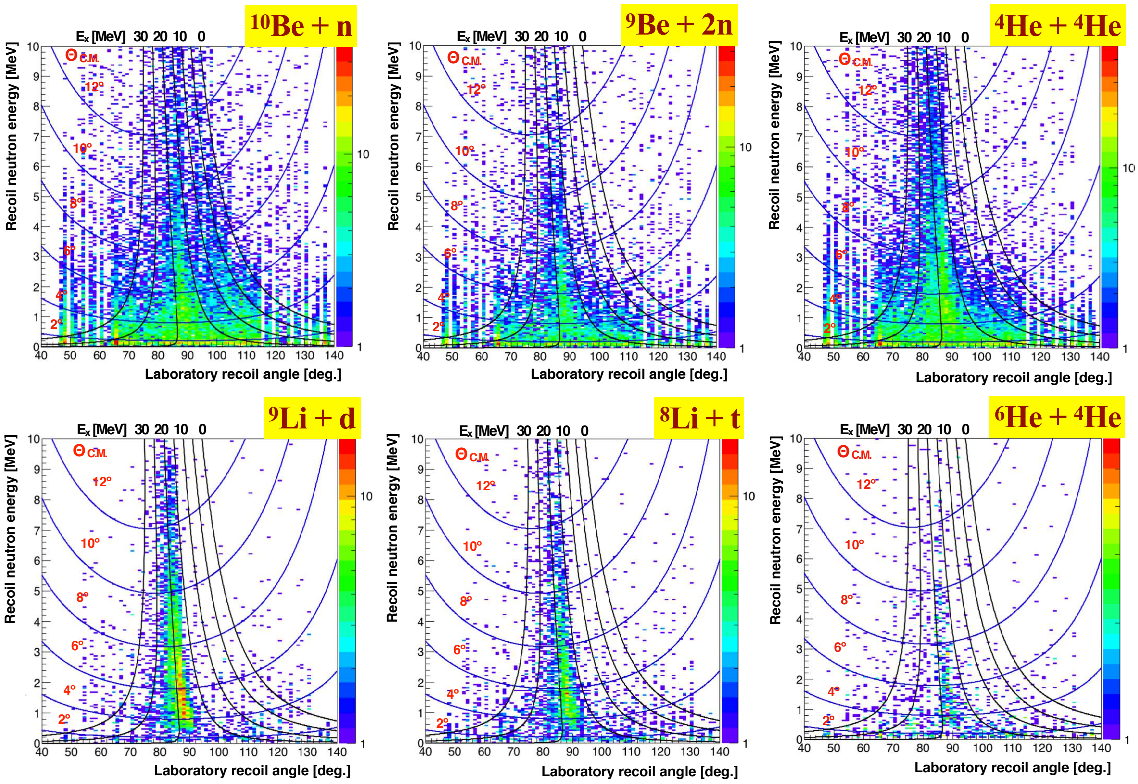

Figure 4. The neutron kinetic energy (E$_n$) vs. laboratory scattering angle (θ_{lab}) correlations for different decay channels of ^{11}Be reaction product.

4. Correlations of neutron energy and laboratory scattering angle correlations

Figure 4 shows a summary of plots of kinetic energy (E_n) as a function of laboratory scattering angle (θ_{lab}) for recoil neutrons associated with the ^{11}Li-beam component. Scatter plots are shown separately for different residue species (decay channels) detected in the spectrometer. Owing to the large momentum acceptance of SAMURAI, the trajectories of the fragments associated with the decay by $1n$, $2n$, t, d, 2α and ^{6}He+α emissions of the beam residues produced by the (p, n) reactions were measured in a single magnetic-field setting with reasonable resolution. Clear kinematical correlations are visible between E_n and (θ_{lab}) around 20 MeV excitation energy for the different decay channels of ^{11}Be produced by the ^{11}Li(p, n) reaction. These forward-scattering peaks (2°-7° in the center-of-mass system) suggest Gamow-Teller transitions. Reconstruction of the excitation-energy spectrum up to about 30 MeV, including the Gamow-Teller giant resonance region is ongoing.

5. Summary

Our new low-energy neutron detector, PANDORA and its digital data-acquisition system were combined with the standard analog data acquisition of SAMURAI in order to perform (p, n) reactions in inverse kinematics for light, neutron-drip-line nuclei for the first time. In the ^{11}Li$(p, n)^{11}$Be reaction, PANDORA was used for detecting recoil neutrons and SAMURAI was used for tagging the decay channel of reaction residues. The neutron-gamma discrimination capability of PANDORA was demonstrated with the ^{11}Li$(p, n)^{11}$Be reaction in inverse kinematics at the SAMURAI magnetic spectrometer. We presented clear kinematical correlations between E_n and (θ_{lab}) for the $1n$, $2n$, t, d, 2α and ^{6}He+α decay channels of ^{11}Be reaction product.

Acknowledgments

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