# Search for unbound excited states of deformed halo nucleus $^{31}$Ne using breakup reactions

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The neutron-rich odd nucleus $^{31}$Ne, which is located in the "island of inversion," has drawn much attention owing to its halo properties. Because this nucleus has been found to have a $p$-wave $1n$ halo structure, it is likely to be strongly deformed.[1)] So far its deformation properties have not been experimentally studied with direct methods. No excited states in $^{31}$Ne, which are expected to be located in the unbound region because of its small separation energy ($S_n = 0.15^{+0.16}_{-0.10}$ MeV),[1)] have been studied. This experiment thus aims at studying the excited states which should reflect the rotational band caused by the deformation. In the present study, we applied the invariant mass method to study the unbound states of $^{31}$Ne in the inelastic scattering reaction C($^{31}$Ne, $^{30}$Ne$+n$) and one neutron removal reaction C($^{32}$Ne, $^{30}$Ne$+n$) to produce such excited states. In addition, we performed the Coulomb breakup reaction Pb($^{31}$Ne, $^{30}$Ne$+n$) to obtain further properties of the ground state.

In November 2016, we performed the SAMURAI27 experiment. A $^{48}$Ca primary beam with a high intensity of approximately 400 particle nA was directed to a Be target. Secondary beams of $^{31}$Ne and $^{32}$Ne were produced and separated by BigRIPS. In this experiment, we used two different settings of the BigRIPS for $^{31}$Ne and $^{32}$Ne. The BigRIPS is settings are listed shown in Table 1.

Particle identification (PID) of the secondary beam was performed by the $\Delta E$-TOF-$B\rho$ method. The energy loss $\Delta E$ was determined using an ionization chamber at F13 (ICB). The time of flight TOF was measured using a 3-mm-thick plastic scintillator at F7 and two 0.5-mm-thick plastic scintillators at F13 (SBT). The magnetic rigidity $B\rho$ was calculated from the horizontal position of 3-mm-thick plastic scintillator at F5. Figure 1 shows a resulting PID plot for the $^{31}$Ne beam. The intensity and the purity of the beams are summarized is shown in Table 1.

The secondary beam was transported to the SAMURAI experimental area and impinged on secondary targets at a bombarding energy of 230 MeV/nucleon. We used a 2.15-g/cm$^2$-thick C target for the $^{31}$Ne and $^{32}$Ne beams, and a 2.76-g/cm$^2$-thick Pb target for the $^{31}$Ne beam. Charged particles and neutrons generated by the breakup reactions were analyzed by the SAMURAI spectrometer.[2)] The charged particles were detected by the standard drift chambers of SAMURAI (FDC1 and FDC2) and hodoscope (HODF24). Outgoing neutrons were detected by NeuLAND[3)] and NEBULA, which provide a high neutron efficiency of about 50%. Additionally, CATANA,[4)] a new $\gamma$-ray detector array, was placed around the secondary target. The data analysis is in progress.

Table 1. BigRIPS settings for the $^{31}$Ne and $^{31}$Ne beams and the resultant intensity and purity.

| | $^{31}$Ne | $^{32}$Ne |
|---|---|---|
| Primary Be target (mm) | 15 | 15 |
| F1 slit (mm) | ±120 | ±100 |
| F1 Al wedge (mm) | 8 | 10 |
| F5 slit (mm) | ±110 | ±50 |
| F5 Al wedge (mm) | 8 | 8 |
| Total intensity (cps) | ∼ 1500 | ∼ 100 |
| Purity (%) | 3 | 20 |

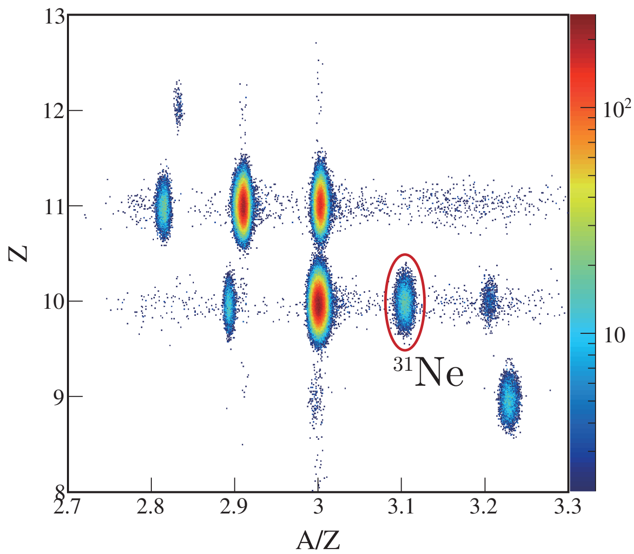


Fig. 1. PID plot for the $^{31}$Ne beam setting. The horizontal axis is mass-to-charge ratio $A/Z$ and the vertical axis is atomic number $Z$.

References
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