Single-Neutron Knockout Reaction from $^{30}$Ne

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Intruder configurations in the ground state of $^{30}$Ne were studied using the one neutron knockout reaction $^{12}$C($^{30}$Ne,$^{29}$Ne+γ)X at 228 MeV/nucleon at the Radioactive Isotope Beam Factory. Individual parallel momentum distributions and partial cross sections were measured by tagging γ rays. A significant population of the $p$-wave intruder state in $^{29}$Ne is observed, providing further experimental evidence for the vanishing of the $N$=20 shell closure.

**KEYWORDS:** intruder configurations, knockout reaction, $^{30}$Ne, $^{29}$Ne

1. Introduction

The evolution from normal to intruder configurations towards the island of inversion [1], a region around neutron-rich $N$=20 nuclei, is important to understand new aspects of the nuclear force [2] in nuclei far from the valley of stability. For Ne isotopes, the onset of intruder configurations was found in $^{28}$Ne, of which a $3/2^-$ component was observed in the ground state [3]. In $^{29}$Ne, an $s$-orbital halo was suggested from the interaction cross section measurement [4]. Very recently, $^{31}$Ne was identified as a deformation-driven $p$-wave halo nucleus [5]. Despite the fact that $N$=20 is a conventional magic number, $^{30}$Ne has been proven to be well deformed by the low excitation energy of the first $2^+$ state and the enhanced $E2$ transition probability [6]. For a more complete understanding of the evolution along the Ne isotopic chain, we studied intruder configurations in the ground state of $^{30}$Ne by means of the one-neutron knockout reaction $^{12}$C($^{30}$Ne,$^{29}$Ne+γ)X.

2. Experimental details

The experiment was carried out at the RIKEN Radioactive Isotope Beam Factory. The secondary beam, which contained $^{30}$Ne among other products, was produced by fragmentation of a $^{48}$Ca primary beam at 345 MeV/nucleon with an average intensity of 75 pnA using a 15-mm-thick rotating beryllium target. The ions of interest, $^{30}$Ne, were selected using the BigRIPS fragment separator [7] by measuring the energy loss ($\Delta E$), magnetic rigidity ($Bp$) and time-of-flight (TOF) before impinging on a 2.54 g/cm$^2$ carbon target. The mid-target energy and intensity of $^{30}$Ne were approximately 228...
MeV/nucleon and 300 particles per second, respectively. Reaction products were transported to the ZeroDegree spectrometer (ZDS) [7] and identified using the $\Delta E-Bp$-TOF method discussed above. Particle identification plots for the incoming beam and outgoing fragments are shown in Fig. 1a and Fig. 1b, respectively.

![Particle identification plots](image)

**Fig. 1.** Particle identification before and after the secondary target. a) Constituents of the secondary beams passing through BigRIPS. b) Reaction products accepted by the ZDS.

The DALI2 detector array [8], consisting of 186 NaI (TI) crystals with an angular coverage of 18°–150° with respect to the beam axis, surrounded the carbon target to detect the de-excitation $\gamma$ rays from the reaction. The Doppler-shift corrected $\gamma$-ray energy spectrum for the one-neutron knockout reaction $^{12}\text{C}(^{30}\text{Ne},^{29}\text{Ne}+\gamma)X$ with $\gamma$-ray multiplicity $M_\gamma=1$ is presented in Fig. 2. Three $\gamma$-ray peaks are present at 231(7), 625(6) and 923(10) keV. No strong $\gamma-\gamma$ coincidence was observed between these transitions, suggesting that all the observed peaks correspond to direct decays to the ground state.

![Doppler-shift corrected γ-ray energy spectrum](image)

**Fig. 2.** Doppler-shift corrected $\gamma$-ray energy spectrum for the one-neutron knockout reaction $^{12}\text{C}(^{30}\text{Ne},^{29}\text{Ne}+\gamma)X$ with $\gamma$-ray multiplicity $M_\gamma=1$. The black solid line shows the result of the total fit to the spectrum. The red and blue dashed lines represent the GEANT4 simulated response functions at the observed transition energies and an exponential fit to the background, respectively.
3. Results and discussion

The $^{29}\text{Ne}$ parallel momentum ($P_{||}$) distribution in the rest frame of $^{30}\text{Ne}$ was extracted from the TOF information obtained at the ZDS and BigRIPS. The inclusive $1n$-removal momentum distribution of $^{29}\text{Ne}$ residues is shown in Fig. 3a. Its width (FWHM) was deduced to be $136(2)\ \text{MeV/c}$ when fitted with a Gaussian function. Such a narrow width is characteristic of a significant population of states with low-$l$ orbitals in $^{29}\text{Ne}$. The momentum resolution was measured by transporting unreacted $^{30}\text{Ne}$ ions to the center of the ZDS. Note that the additional momentum spread stemming from the energy loss difference between $^{30}\text{Ne}$ and $^{29}\text{Ne}$ in the reaction target also needs to be taken into account. As a result, an experimental momentum resolution of $59\ \text{MeV/c}$ (FWHM) was obtained.

![Fig. 3. Parallel momentum distributions of $^{29}\text{Ne}$ residues following the $1n$-removal reaction $^{12}\text{C}(^{30}\text{Ne},^{29}\text{Ne}+\gamma)\ X$. a) Measured inclusive momentum distribution. b) Momentum distribution in coincidence with the 625-keV $\gamma$-ray transition. The blue solid line represents the calculated distribution with assumed angular momentum $l=1$, folded with the experimental resolution.](image)

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<th>$E_{\text{level}}$ (keV)</th>
<th>$\sigma_{\text{exp}}$ (mb)</th>
<th>$l$</th>
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<td>0</td>
<td>25(4)</td>
<td>(1,2)</td>
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<tr>
<td>231</td>
<td>11(2)</td>
<td>(0,1)</td>
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<tr>
<td>625</td>
<td>24(2)</td>
<td>1</td>
</tr>
<tr>
<td>923</td>
<td>2.2(0.4)</td>
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Table I. Measured excitation energies, partial cross sections and $l$ values.

To obtain the strengths from specific orbitals, $\gamma$-ray tagged individual momentum distributions were examined. In the present work, the momentum distributions to the excited levels were extracted by fitting a series of $\gamma$-ray spectra obtained by gating on different regions of the inclusive momentum distribution. The adopted fitting function is a combination of the GEANT4 simulated response functions of DALI2 at the observed transition energies and an exponential background. This technique requires more statistics compared to the method of gating on the photopeaks, but it is more reliable when the peak-to-background ratio of the state of interest is low. The ground-state distribution was then reconstructed by subtracting the excited-state contributions from the inclusive momentum spectrum. The measured individual momentum distributions were then compared with the calculated
curves using the eikonal theory [9] assuming different $l$-values for the removed neutron. Note that the theoretical distributions have been folded with the experimental momentum resolution. From Fig. 3b, it is apparent that the distribution in coincidence with the 625-keV $\gamma$ line is reproduced well by the curve with $l=1$. In addition, a $3/2^-$ state at 656 keV is predicted by the shell model with the SDPF-M interaction [10], showing consistency with the observation. Therefore, the 625-keV excited state was assigned as the $3/2^-$ level. The measured $l$ values for all observed states are listed in Table 1.

The inclusive one-neutron removal cross section is 62(2) mb, which corresponds to 68(2)% of the prediction from the SDPF-M shell model. The partial cross sections to the individual final states were deduced from the $\gamma$-ray intensities in the $\gamma$-ray spectrum with all $\gamma$-ray multiplicities. The results are also summarized in Table 1.

As shown in Table 1, the population of states with $l=1$ orbital in $^{29}$Ne is significant, suggesting the breaking of the $N=20$ shell closure.

4. Acknowledgment

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References