The unbound excited states of the most neutron-rich dripline oxygen isotope, $^{24}$O, have been investigated by using the $^{24}$O($p,p'$)$^{24}$O* reaction at the beam energy of 62 MeV/nucleon in inverse kinematics. The first and second unbound excited states of $^{24}$O have been observed at $E_x = 4.63^{+0.30}_{-0.14}$ MeV and $E_x = 5.13^{+0.19}_{-0.24}$ MeV (preliminary) along with the evidence for another higher lying state at around 7.3 MeV. The quadrupole deformation parameter $\beta_{2+}$ was deduced to be $0.15^{+0.08}_{-0.03}$ (preliminary) for the first time. The systematics of the $\beta_{2+}$ and the $E_x(2^+_1)$ in the $Z = 8$ isotopes shows the $N = 16$ spherical shell closure in $^{24}$O.
1 Introduction

In the oxygen isotopes, new shell closures at $N = 14$ [1–3] and 16 [4–9] have been extensively studied near the neutron drip line both experimentally and theoretically. The measured low $E2$ transition probability, $B(E2)$, and high $2^+_1$ energy in $^{22}$O [1] give the evidence for the $N = 14$ shell closure. However, since the $E2$ transition dose not provide the direct evidence for the small neutron collectivity due to the fact that the $B(E2)$ value depends only on the proton quadrupole matrix element $M_p$, the proton inelastic scattering, which is sensitive to the neutron collectivity at several tens of MeV, has been performed by Becheva et al. [3] to extract the quadrupole deformation parameter of $^{22}$O, and they reported the small deformation of $\beta_{2+} = 0.26 \pm 0.04$ strongly supporting the $N = 14$ spherical shell closure.

Recently, the first experimental attempt to measure the $2^+_1$ energy of $^{24}$O was made by Hoffman et al. [8] at MSU using the proton removal reaction of a $^{26}$F beam. Since no $\gamma$-ray decay was observed [2], they used the invariant mass method to measure the unbound excited states of $^{24}$O. Although the measured high energy for the first excited state in $^{24}$O supports the magic nature of this isotope at $N = 16$, the degree of collectivity has still not been experimentally determined.

We report on the quadrupole deformation parameter $\beta_{2+}$ in $^{24}$O for the first time. The resonance energies of the unbound excited states of $^{24}$O were measured by the invariant mass method in inverse kinematics, and the $\beta_{2+}$ value was deduced by a phenomenological analysis. Our results show the experimental evidence for the $N = 16$ spherical shell closure in the oxygen isotopes.

2 Experiment

The experiment was performed at the RIPS facility [10] operated by the RIKEN Nishina Center. The secondary beam of $^{24}$O was produced in a 1.5 mm-thick Be production target by the fragmentation of a 95 MeV/nucleon $^{40}$Ar primary beam. The typical intensity of the $^{24}$O beam was about 4 ions/sec. The secondary beam was selected by magnetic analysis in the fragment separator, RIPS, and the magnetic rigidity was determined from the position measurements in parallel plate avalanche counters (PPAC) mounted at the dispersive focus F1. The time of flight was determined from a time difference between a thin plastic scintillator mounted at the achromatic focus F2 and a RF signal provided by the AVF and the Ring cyclotron. The energy loss of the secondary beam was measured by a 350 $\mu$m-thick silicon detector mounted at the achromatic focus F2. Particle identification of the secondary beam was performed by the $B_\rho$-TOF-$\Delta E$ method. The liquid-hydrogen experimental target [11] was installed at the achromatic focus F3.

A schematic view of the experimental setup is shown in Fig. 1. The trajectory of the secondary beam was determined by tracking of two drift chambers (NDCs) installed in front of the liquid-hydrogen target. The positions and angles on the experimental target were extrapolated by tracking of the NDCs. The charged fragments emitted from the target were bent by a dipole magnet placed downstream of the target, and their trajectories were measured by two drift chambers, MDC and FDC, placed before and after the dipole magnet, respectively. The energy loss of the fragment was measured in the charged particle hodoscope installed just after the FDC. The mass and charge of the fragment were identified by employing the $B_\rho$-TOF-$\Delta E$ method.

Neutrons were detected by a neutron counter array placed about 4.7 m downstream from the target. To exclude all charged particles emerging from the target, the veto-counter was installed just before the neutron counter array. A schematic view of the experimental setup is shown in Fig. 1.
3 Results

The decay energy of $^{24}\text{O}^*$ (relative kinetic energy between $^{23}\text{O}$ and $n$) was reconstructed by measuring the four momenta of $^{23}\text{O}$ and $n$, and is expressed as

$$E_{\text{decay}} = \sqrt{(E_f + E_n)^2 - |P_f + P_n|^2 - (M_f + M_n)}.$$  \hfill (1)

where $E_f (E_n)$ and $P_f (P_n)$ are the total energy and momentum vector of $^{23}\text{O}$ (neutron), respectively. The $M_f$ and $M_n$ are the masses of $^{23}\text{O}$ and neutron, respectively.

The cross section, $d\sigma/dE$, is shown by the data points in Fig. 2, where the error bars are statistical ones. We assumed that the first peak is of two nearby resonances due to the fact that the width of the observed peak at $E_{\text{decay}} \sim 0.7$ is wider than the experimental energy resolution by about factor of 2. The best fit to the experimental data is shown by the solid histogram. The peak areas corresponding to the first and the second excited states are shown by the shaded and dashed histograms at $E_{\text{decay}} \sim 0.5$ and $\sim 1$ MeV, respectively, which were generated by the Monte-Carlo simulation taking into account the experimental resolutions and beam profile. In the simulation, the energy dependent Breit–Wigner line shapes assuming the $d$-wave neutron were used to generate the resonance shapes of the states:

$$\sigma_l \sim \frac{\Gamma_l(E_{\text{decay}})}{(E_{\text{decay}} - E_r)^2 + \frac{1}{4}\Gamma_r^2(E_{\text{decay}})}.$$  \hfill (2)

where $E_r$ and $\Gamma_r$ are the resonance energy and level width. The energy dependent width $\Gamma_l(E_{\text{decay}})$ was calculated from the penetrability factor $P_l$ in Ref. [12]: $\Gamma_l(E_{\text{decay}}) = \Gamma_r P_l(E_{\text{decay}})/P_l(E_r)$. A high lying state at $E_{\text{decay}} \sim 3.2$ MeV, which has been recently reported in Ref. [13], is shown by the dotted line. The Gaussian function was used to describe the high lying state. The dot-dashed curve represents the Maxwellian background proposed in Ref. [14].

The spin parity of the first excited state of $^{24}\text{O}$ is expected to be $1^+_1$ or $2^+_1$ with the configuration of $(\nu0d_{3/2})^{1}\otimes(\nu1s_{1/2})^{-1}$ in the naive single particle picture. The theoretical calculations using the universal $sd$ shell-model interactions, such as USD [15] and USD(ab) [16], as well as the shell model including the continuum states [17] predict that the $2^+_1$ state lies about 0.5–1.0 MeV below the $1^+_1$ state. It is most likely that the first peak at $E_{\text{decay}} \sim 0.5$ MeV is that of the $2^+_1$ state.
The fit was performed to find the \( \chi^2 \) minimum by varying values of \( E_r(2^+_1), E_r(1^+_1), \Gamma_r(2^+_1), \) and \( \Gamma_r(1^+_1) \). The extracted resonance energies of the \( 2^+_1 \) and \( 1^+_1 \) states are \( E_r(2^+_1) = 0.54^{+0.27}_{-0.06} \text{ MeV} \) and \( E_r(1^+_1) = 1.04^{+0.14}_{-0.20} \text{ MeV} \), with the level widths of \( \Gamma_r(2^+_1) = 0.04^{+1.76}_{-0.04} \text{ MeV} \) and \( \Gamma_r(1^+_1) = 0.24^{+1.06}_{-0.24} \text{ MeV} \), respectively. The corresponding excitation energies are \( 4.63^{+0.30}_{-0.10} \text{ MeV} \) and \( 5.13^{+0.19}_{-0.22} \text{ MeV} \) by adopting \( S_0 = 4.09 \pm 0.13 \text{ MeV} \) [18]. This result is consistent with the previous measurement [8]. The high lying state at \( E_{\text{decay}} \sim 3.2 \text{ MeV} \) corresponds to the excitation energy of \( E_x \sim 7.3 \text{ MeV} \). The large errors in the level widths are due to the fact that the peak width is dominated by the experimental resolution, as well as the low statistics.

The cross sections of the \( 2^+_1 \) and \( 1^+_1 \) states were extracted to be \( \sigma_{2^+_1} = 2.66^{+3.45}_{-0.79} \text{ mb} \) and \( \sigma_{1^+_1} = 2.97^{+1.99}_{-1.64} \text{ mb} \), respectively, by integrations of the peak areas in Fig. 2. The quoted errors are due mostly to the uncertainties of \( E_r \) and \( \Gamma_r \), and contain the systematic errors (\( \sim 7\% \) in \( \sigma_{2^+_1} \) and \( \sim 10\% \) in \( \sigma_{1^+_1} \)). The major systematic errors are due to the choice of function forms describing the background (\( \sim 6\% \) in \( \sigma_{2^+_1} \)) and high lying state (\( \sim 8\% \) in \( \sigma_{1^+_1} \)).

For extracting the deformation parameter, DWBA calculations were carried out with the coupled-channel calculation code ECIS97 [19] using the standard symmetric vibrational model for two sets of global phenomenological potentials KD02 [20] and CH89 [21]. The results of DWBA calculations with the potentials were in good agreement with the \( ^{24}\text{O} \) data that were previously obtained by proton inelastic scattering in Ref. [3]. The \( \beta_2^+ \) values were deduced by normalization of the calculated inelastic cross sections to the \( \sigma_{2^+_1} \), and we adopted the average value of \( \beta_2^+ = 0.15^{+0.08}_{-0.03} \). The quoted error reflects the uncertainty in the experimental cross section with additional uncertainty (5\%) due to the choice of the optical parameters.

4 Summary

In summary, we have investigated the unbound excited states of \( ^{24}\text{O} \) using the invariant mass method in the \( ^{23}\text{O} \) decay channel via the proton inelastic scattering in inverse kinematics. The first and second excited states of \( ^{24}\text{O} \) have been observed at the energies of \( E_x = 4.63^{+0.30}_{-0.14} \text{ MeV} \) and \( E_x = 5.13^{+0.19}_{-0.24} \text{ MeV} \) (preliminary), respectively, which are consistent with those of the previous measurement [8]. The quadrupole deformation parameter in \( ^{24}\text{O} \) was deduced to be \( \beta_2^+ = 0.15^{+0.08}_{-0.03} \) (preliminary) for the first time. The results strongly support the \( N = 16 \) spherical shell closure in the \( Z = 8 \) isotopes.

Acknowledgments We would like to thank the accelerator staff of RIKEN for their excellent operation. This work is supported by the Grant-in-Aid for Scientific Research (No. 19740133) from MEXT Japan, and WCU program and the Grant 2010-002452 of NRF Korea. D. Sohler was supported by Bolyai Foundation and OTKA K68801.

References

1. Thirolf, P.G., et al.: Spectroscopy of the \( 2^+_1 \) state in \( ^{22}\text{O} \) and shell structure near the neutron drip line. Phys. Lett. B 485, 16 (2000)
2. Stanou, M., et al.: \( N = 14 \) and 16 shell gaps in neutron-rich oxygen isotopes. Phys. Rev. C 69, 034312 (2004)
3. Becheva, E., et al.: \( N=14 \) Shell closure in \( ^{22}\text{O} \) viewed through a neutron sensitive probe. Phys. Rev. Lett. 96, 012501 (2006)
4. Ozawa, A., et al.: New magic number, \( N = 16 \), near the neutron drip line. Phys. Rev. Lett. 87, 5493 (2000)
5. Kanungo, R., Tanihata, I., Ozawa, A.: Observation of new neutron and proton magic numbers. Phys. Lett. B 528, 58 (2002)
6. Otsuka, T., et al.: Magic numbers in exotic nuclei and spin–isospin properties of the NN interaction. Phys. Rev. Lett. 87, 082502 (2001)
7. Hoffman, C.R., et al.: Determination of the \( N=16 \) shell closure at the oxygen drip line. Phys. Rev. Lett. 100, 152502 (2008)
8. Hoffman, C.R., et al.: Evidence for a doubly magic \( ^{24}\text{O} \). Phys. Lett. B 672, 17 (2009)
9. Kanungo, R., et al.: One-neutron removal measurement reveals \( ^{24}\text{O} \) as a new doubly magic nucleus. Phys. Rev. Lett. 102, 152501 (2009)
10. Kubo, T., et al.: The RIKEN radioactive beam facility. Nucl. Instrum. Methods Phys. Res. B 70, 309 (1992)
11. Ryuto, H., et al.: Liquid hydrogen and helium targets for radioisotope beams at RIKEN. Nucl. Instrum. Methods Phys. Res. A 555, 1 (2005)
12. Lane, A.M., Thomas, R.G.: R-matrix theory of nuclear reactions. Rev. Mod. Phys. 30, 257 (1958)
13. Hoffman, C.R., et al.: Observation of a two-neutron cascade from a resonance in \( ^{24}\text{O} \). Phys. Rev. C 83, 031303(R) (2011)
14. Deák, F., et al.: Method for the study of neutron emission from light fragments in intermediate energy heavy-ion collisions. Nucl. Instrum. Methods Phys. Res. Sect. A 258, 67 (1987)
15. Brown, B.A., Wildenthal, B.: Status of the nuclear shell model. Annu. Rev. Nucl. Part. Sci. 38, 29 (1988)
16. Brown, B.A., Richter, W.A.: New USD Hamiltonians for the \( sd \) shell. Phys. Rev. C 74, 034315 (2006)
17. Volya, A., Zelevinsky, V.: Discrete and continuum spectra in the unified shell model approach. Phys. Rev. Lett. 94, 052501 (2005)
18. Jurado, B., et al.: Mass measurements of neutron-rich nuclei near the \(N=20\) and \(28\) shell closures. Phys. Lett. B 649, 43 (2007)
19. Raynal, J.: Coupled channel code ECC97 (unpublished)
20. Koning, A.J., Delaroche, J.P.: Local and global nucleon optical models from 1 keV to 200 MeV. Nucl. Phys. A 713, 231 (2003)
21. Varner, R.L., et al.: A global nucleon optical model potential. Phys. Rep. 201, 57 (1991)