EPJ Web of Conferences 66, 02103 (2014)
DOI: 10.1051/epjconf/20146602103

Neutron occupancy of $0d_{5/2}$ orbital in ^{24}O

K. Tshoo[1,a], Y. Satou[2], H. Bhang[2], S. Choi[2], T. Nakamura[3], Y. Kondo[3], S. Deguchi[3], Y. Kawada[3], N. Kobayashi[13], Y. Nakayama[3], K.N. Tanaka[3], N. Tanaka[3], Y. Togano[3], N. Aoi[12], M. Ishihara[4], T. Motobayashi[4], H. Otsu[4], H. Sakurai[4], S. Takeuchi[4], K. Yoneda[4], F. Delaunay[5], J. Gibelin[5], F.M. Marqués[5], N.A. Orr[5], T. Honda[6], M. Matsushita[9], T. Kobayashi[7], Y. Miyashita[8], T. Sumikama[7], K. Yoshinaga[8], S. Shimoura[9], D. Sohler[10], T. Zheng[11], Z.X. Cao[11], and Z.H. Li[11]

[1] *RISP, Institute for Basic Science, 70, Yusung-gu, Daejeon 305-811, Korea.*
[2] *Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea.*
[3] *Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan.*
[4] *RIKEN Nishina Center, Saitama 351-0198, Japan.*
[5] *LPC-Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, 14050 Caen cedex, France.*
[6] *Department of Physics, Rikkyo University, Tokyo 171-8501, Japan.*
[7] *Department of Physics, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan.*
[8] *Department of Physics, Tokyo University of Science, Noda, Chiba 278-8510, Japan.*
[9] *Center for Nuclear Study, University of Tokyo, Saitama 351-0198, Japan.*
[10] *Institute for Nuclear Research of the Hungarian Academy of Sciences, P.O.Box 51, H-4001 Debrecen, Hungary.*
[11] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China.*
[12] *Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan.*
[13] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan.*

Abstract. The partial one-neutron removal cross section of ^{24}O leading to the first excited state in ^{23}O has been measured to be 65.7 ± 5.3 mb with a proton target in inverse kinematics at the beam energy of 62 MeV/nucleon. The decay energy spectrum of the neutron unbound state of ^{23}O was reconstructed from the measured four momenta of ^{22}O and the emitted neutron. A sharp peak was observed at $E_{\text{decay}} = 48 \pm 3$ keV, confirming the previous measurements. The measured partial longitudinal momentum distribution of ^{23}O* showed the d-wave knockout character, providing a support for the J^π assignment of $5/2^+$ for this state. The spectroscopic factor for the neutrons in $0d_{5/2}$ orbital was deduced, for the first time, to be $C^2S(0d_{5/2}) = 3.7 \pm 0.3$ (preliminary) by comparing with the result of Glauber model. The relatively large spectroscopic factor supports the $N = 16$ shell closure in the neutron drip-line nucleus ^{24}O.

Magic numbers (2, 8, 20, 28, . . .) in nuclei near the β-stability were key feature to understand the many-body quantum system over the past few decades. Thanks to recent developments in radioactive ion-beam technique, the proton- and neutron-rich nuclei have been extensively studied, and the changing of magic numbers was discovered as the proton or neutron drip lines are approached. The $N = 16$ neutron drip-line nucleus ^{24}O, which has been studied extensively in Refs. [1–6], was suggested as a new doubly closed shell nucleus. The high excitation energy of the first 2^+ state and the small

[a] e-mail: tshoo@ibs.re.kr

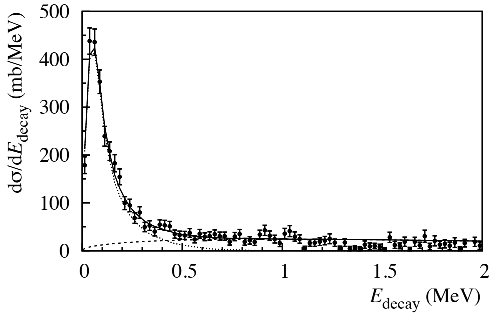

Figure 1. The cross section, $d\sigma/dE_{\rm decay}$, by measuring a neutron in coincidence with ^{22}O. The error bars are statistical only. The dotted and dashed lines are the results of fits for a resonance at $E_{\rm decay}$ = 48 keV and a non-resonant continuum component [10], respectively.

quadrupole transition parameter β_2 of ^{24}O are indicative of the $N = 16$ spherical shell closure [6]. Other confirmation of the spherical shell closure is to measure nucleon occupancies. R. Kanungo *et. al.* [4] confirmed the $N = 16$ spherical shell closure of ^{24}O from the measurement of large spectroscopic factor $C^2S(1s_{1/2}) = 1.74 \pm 0.19$ reflecting the occupation number of the neutrons in $1s_{1/2}$ orbital. In this paper, we report on the spectroscopic factor $C^2S(0d_{5/2})$ for the neutrons in the ground state of ^{24}O. The $0d_{5/2}$ neutron hole state of ^{23}O, which is a neutron unbound state, was populated by the one-neutron removal reaction of ^{24}O with a proton target. The excitation energy and the longitudinal momentum distribution of ^{23}O* have been measured to identify the $0d_{5/2}$ neutron hole state. A relatively large spectroscopic factor is indicative of a strong neutron occupancy in $0d_{5/2}$ orbital, providing a support of the $N = 16$ spherical shell closure in ^{24}O.

The experiment was performed at the RIPS facility [7] at RIKEN. The experimental setup has been described in Refs. [6, 8]. The secondary ^{24}O beam was produced using a 1.5 mm-thick Be production target and a 95 MeV/nucleon ^{40}Ar primary beam. The liquid-hydrogen (LH_2) target [9] was installed at the achromatic focus F3 of RIPS. The $B\rho$-TOF-ΔE method was employed to identify the charged fragments following reactions of the ^{24}O beam with the LH_2 target. The magnetic rigidity ($B\rho$) was determined from the position and angle measurements derived from two multi-wire drift chambers placed at the entrance and exit of the dipole magnet. The time-of-flight (TOF) of the fragments was measured between the target and the plastic scintillator charged particle hodoscope. The energy loss (ΔE) was measured using the charged particle hodoscope. The neutrons were detected using the plastic scintillator neutron counter array placed some 4.7 m downstream of the target together with the charged particle veto counter.

The decay energy spectrum of ^{23}O* was reconstructed from the measured four momenta of ^{22}O and the emitted neutron. The decay energy $E_{\rm decay}$ is expressed as: $E_{\rm decay} = [(E_f + E_n)^2 - |\boldsymbol{p}_f + \boldsymbol{p}_n|^2]^{1/2} - (M_f + M_n)$, where E_f (E_n), $\boldsymbol{p}_f$ ($\boldsymbol{p}_n$), and M_f (M_n) are the total energy, the momentum and the masses of ^{22}O (neutron), respectively. Figure 1 shows the decay energy spectrum in terms of cross section ($d\sigma/dE_{\rm decay}$) after correction for the detection efficiencies and acceptances. The error bars are statistical only. The geometrical acceptance was estimated using a Monte Carlo simulation taking into account the beam profile, the geometry of the setup, the experimental resolutions, and multiple scattering of the charged particles. The decay energy spectrum was described using one resonance for the peak at $E_{\rm decay}$ = 48 keV and a Maxwellian distribution for the non-resonant continuum [10]. Since the observed peak width is dominated by the experimental resolution, the experimental resolution was adopted for the width. The dotted and dashed lines correspond to the resonance at $E_{\rm decay} = 48 \pm 3$ keV, which corresponds to $E_{\rm x} = 2.79 \pm 0.13$ MeV adopting a separation energy $S_n(^{23}\mathrm{O}) = 2.74 \pm 0.13$ MeV [11], and the background, respectively. The decay energy of the first excited state is in good agreement with the previous experiments [12, 13].

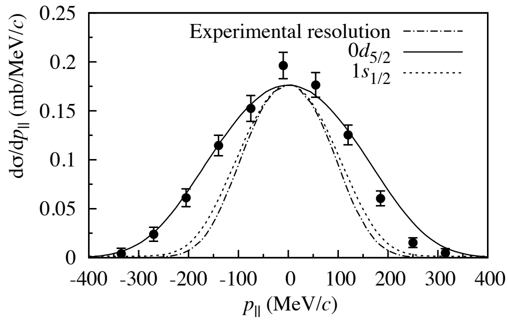

Figure 2. The longitudinal momentum distribution of $^{23}O^*$ populated in the first $5/2^+$ state in the beam rest frame. The error bars are statistical only. The solid and dotted lines represent the calculated longitudinal momentum distributions for the $0d_{5/2}$ and $1s_{1/2}$ knocked-out neutrons, respectively. The dot-dashed line corresponds to the simulated momentum resolution.

Table 1. The spectroscopic factors for $^{24}O \rightarrow {}^{23}O$ and the excitation energy of the first $5/2^+$ state in ^{23}O are compared with the results of the USDB shell-model calculation.

	Energy (MeV)		C^2S	
J^π	Exp	USDB	Exp	USDB
$1/2^+$	0.0	0.0	1.74 ± 0.19^a	1.81
$5/2^+$	2.79 ± 0.13	2.59	3.7 ± 0.3	5.67

^{a} From Ref. [4].

The one-neutron removal cross section to the resonance at $E_{\rm decay}$ = 48 keV was extracted to be $\sigma^{\rm exp}_{-n}$ = 65.7 ± 5.3 mb. The quoted error mainly comes from the uncertainty in the choice of the functional form describing the non-resonant continuum and the statistical uncertainty. The experimentally determined one-neutron removal cross section has been compared with reaction model calculation based on the Glauber approximation [14]. In the calculation, the single particle cross section was calculated using the code csc_gm [15] by taking into account both stripping and diffractive knockout processes. The wave functions of single particle neutron orbits in the core were calculated using the Woods-Saxon potential. The Skyrme (SkX) Hartree-Fock (HF) calculation [16] was employed to deduce the root-mean-squared (rms) radius $r_{\rm HF}$ of each single-particle orbit in the projectile using the code nushell [17]. The reduced radius r_0 and the depth of the potential were chosen to reproduce $r_{\rm sp}$ and $S_n^{\rm eff}$ (effective neutron separation energy), respectively, where $r_{\rm sp} = \sqrt{A/(A-1)}\, r_{\rm HF}$. The $S_n^{\rm eff}$ was calculated to be 6.88 MeV adopting $S_n(^{24}O)$ = 4.09 ± 0.13 MeV [18]. The elastic S-matrix for the proton-neutron (proton-core) scattering was calculated by the finite-range Gaussian profile function [19] with a nucleon density of the core obtained from the HF calculation. The theoretical one-neutron removal cross section was calculated to be $\sigma^{\rm th}_{-n}(0d_{5/2})$ = 99.39 mb by employing the shell-model spectroscopic factor of $C^2S^{\rm th}$ = 5.67 obtained by using the USDB interaction [20]. The experimental spectroscopic factor was determined to be $C^2S^{\rm exp}(0d_{5/2})$ = 3.7 ± 0.3 (preliminary). The reduction factor defined as $R_s = C^2S^{\rm exp}/C^2S^{\rm th}$ was deduced to be R_s = 0.66 ± 0.05. A similar value of R_s = 0.70 ± 0.06 has been reported in the N =14 closed shell nucleus ^{22}O [21] via inclusive one-neutron knockout reaction. Figure 2 shows the longitudinal momentum distribution ($p_{\|}$) of $^{23}O^*$ in the beam rest frame. The momentum distribution was deduced by fitting the decay energy spectrum for each momentum bin in the same manner as for Fig. 1, and is compared with the results of the Glauber-model calculations performed using the code csc_gm, with only the stripping reaction mechanism being taken into account. The calculated distributions were convoluted with the experimental momentum resolution of 204 MeV/c in FWHM determined by a Gaussian fit to the simulated distribution. The solid and dotted lines represent the calculated longitudinal momentum distributions for the $0d_{5/2}$ and $1s_{1/2}$ knocked-out neutrons, respectively. The dot-dashed line corresponds to the simulated momentum resolution. The calculated result for the $0d_{5/2}$ knockout neutron reproduces the momentum distribution of the resonance at $E_{\rm decay}$ = 48 keV well, supporting the spin-parity assignment of $J^\pi = 5/2^+$ for the first excited state of ^{23}O. This state has also been measured via a different reaction channel, proton inelastic scattering, in separate ^{23}O beam runs in this experiment, and the same J^π assignment has been proposed [13].

The spectroscopic factors for the neutrons in ^{24}O and the excitation energies of ^{23}O are compared with the results of the USDB shell-model calculation in Table 1. The USDB shell model well reproduces the energy and the quadrupole transition parameter of the first excited states of ^{22,24}O in Refs. [6, 22], predicting the N = 14 and 16 shell closures in oxygen isotopes. The measured spectroscopic factors are in agreement with those of the USDB shell model, if we include the reduction factor of $R_s \sim 0.7{-}0.8$ as suggested from the systematics reported in Ref. [21]. The relatively large neutron spectroscopic factors for both $1s_{1/2}$ and $0d_{5/2}$ orbitals show strong neutron occupancies in $1s_{1/2}$ and $0d_{5/2}$ orbitals, thereby supporting the large shell gap between the $1s_{1/2}$ and $0d_{3/2}$ orbitals.

In summary, we have investigated the neutron spectroscopic factor for the $0d_{5/2}$ orbital in ^{24}O via one-neutron removal reaction with a proton target. The excitation energy of the first excited state of ^{23}O was measured to be 2.79 ± 0.13 MeV and the spin-parity was assigned to be $J^\pi = 5/2^+$ from the measurement of the longitudinal momentum distribution of ^{23}O*. The relatively large neutron spectroscopic factor, $C^2S^{\rm exp}(0d_{5/2}) = 3.7 \pm 0.3$, supports the N = 16 spherical shell closure in ^{24}O.

Acknowledgments

We would like to thank the accelerator operations staff of RIKEN for providing the ^{40}Ar beam. This work is supported by the Grant-in-Aid for Scientific Research (No. 19740133) from MEXT Japan, the WCU program and Grant 2010-0024521 of the NRF Korea.

References

[1] A. Ozawa *et al.*, Phys. Rev. Lett. **84**, 5493 (2000).
[2] B.A Brown and W.A. Richter, Phys. Rev. C **72**, 057301 (2005).
[3] C.R. Hoffman *et al.*, Phys. Lett. B **672**, 17 (2009).
[4] R. Kanungo *et al.*, Phys. Rev. Lett. **102**, 152501 (2009).
[5] T. Otsuka *et al.*, Phys. Rev. Lett. **105**, 032501 (2010).
[6] K. Tshoo *et al.*, Phys. Rev. Lett. **109**, 022501 (2012).
[7] T. Kubo *et al.*, Nucl. Instr. Meth. B **70**, 309 (1992).
[8] Y. Satou *et al.*, Phys. Lett. B **660**, 320 (2008).
[9] H. Ryuto *et al.*, Nucl. Instr. Meth. A **555**, 1 (2005).
[10] F. Deák *et al.*, Nucl. Instr. Meth. A **258**, 67 (1987).
[11] G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337 (2003).
[12] A. Schiller *et al.*, Phys. Rev. Lett. **99**, 112501 (2007).
[13] Y. Satou *et al.*, Few-Body Syst. **54**, 287 (2013).
[14] P.G. Hansen and J.A. Tostevin, Annu. Rev. Nucl. Part. Sci. **53**, 219 (2003).
[15] B. Abu-Ibrahim *et al.*, Comp. Phys. Comm. **151**, 369 (2003).
[16] B.A. Brown, Phys. Rev. C **58**, 220 (1998).
[17] B.A. Brown and W.D.M. Rae, MSU-NSCL report (2007).
[18] B. Jurado *et al.*, Phys. Lett. B **649**, 43 (2007).
[19] B. Abu-Ibrahim *et al.*, Phys. Rev. C **77**, 034607 (2008).
[20] B.A. Brown and W.A. Richter, Phys. Rev. C **74**, 034315 (2006).
[21] A. Gade *et al.*, Phys. Rev. Lett. **93**, 042501 (2004).
[22] E. Becheva *et al.*, Phys. Rev. Lett. **96**, 012501 (2006).