Spectroscopic Study of Neutron Shell Closures via Nucleon Transfer in the Near-Dripline Nucleus ^{23}O

Z. Elekes,[1,2] Zs. Dombrádi,[1] N. Aoi,[2] S. Bishop,[2] Zs. Fülöp,[1] J. Gibelin,[3] T. Gomi,[2] Y. Hashimoto,[4] N. Imai,[2] N. Iwasa,[5] H. Iwasaki,[6] G. Kalinka,[1] Y. Kondo,[4] A. A. Korsheninnikov,[2,7] K. Kurita,[8] M. Kurokawa,[2] N. Matsui,[4] T. Motobayashi,[2] T. Nakamura,[4] T. Nakao,[6] E. Yu. Nikolskii,[2,7] T. K. Ohnishi,[6] T. Okumura,[4] S. Ota,[9] A. Perera,[2] A. Saito,[6] H. Sakurai,[2] Y. Satou,[4] D. Sohler,[1] T. Sumikama,[2] D. Suzuki,[6] M. Suzuki,[6] H. Takeda,[9] S. Takeuchi,[2] Y. Togano,[8] and Y. Yanagisawa[2]

[1]*Institute of Nuclear Research of the Hungarian Academy of Sciences, P.O. Box 51, Debrecen, H-4001, Hungary*
[2]*The Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*Institut de Physique Nucléaire, 15 rue Georges Clemenceau 91406 Orsay, France*
[4]*Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan*
[5]*Tohoku University, Sendai, Miyagi 9808578, Japan*
[6]*University of Tokyo, Tokyo 1130033, Japan*
[7]*Kurchatov Institute, Kurchatov sq. 1, 123182, Moscow, Russia*
[8]*Rikkyo University, 3 Nishi-Ikebukuro, Toshima, Tokyo 171, Japan*
[9]*Kyoto University, Kyoto 606-8501, Japan*

(Received 30 November 2006; published 8 March 2007)

Neutron single particle energies have been measured in ^{23}O using the ^{22}O$(d, p)^{23}$O$^* \rightarrow {}^{22}$O $+ n$ process. The energies of the resonant states have been deduced to be 4.00(2) MeV and 5.30(4) MeV. The first excited state can be assigned to the $\nu d_{3/2}$ single particle state from a comparison with shell model calculations. The measured 4.0 MeV energy difference between the $\nu s_{1/2}$ and $\nu d_{3/2}$ states gives the size of the $N = 16$ shell gap which is in agreement with the recent USD05 (''universal'' sd from 2005) shell model calculation, and is large enough to explain the unbound nature of the oxygen isotopes heavier than $A = 24$. The resonance detected at 5.3 MeV can be assigned to a state out of the *sd* shell model space. Its energy corresponds to a $\sim$1.3 MeV sized $N = 20$ shell gap, therefore, the $N = 20$ shell closure disappears at $Z = 8$ in agreement with Monte Carlo shell model calculations using SDPF-M interaction.

DOI: 10.1103/PhysRevLett.98.102502 PACS numbers: 21.10.Pc, 25.45.Hi, 25.60.Je, 27.30.+t

The question of the nuclear shell structure stability at the driplines is fundamental and has a leading role in nuclear physics research [1,2]. The stability of the shell closures is marked by the size of the shell gaps measured as the energy difference between the single particle states belonging to different major shells. By changing the number of protons and/or neutrons in the atomic nucleus, the energy of the single particle states, and, consequently, the size of the shell gaps also alters due to the interaction between protons and neutrons. Otsuka *et al.* [3] pointed out the possible role of the monopole component of this interaction in determining the magnitude of the change. For instance, a dramatic shift of the single particle energies is predicted by moving from ^{30}Si to ^{24}O due to the strong tensor interaction between the $d_{5/2}$ protons and the $d_{3/2}$ neutrons [3]: While removing protons from the $\pi d_{5/2}$ orbital, the energy of the neutron $d_{3/2}$ state (originally close to the $\nu s_{1/2}$ state) is increased so much that when the $\pi d_{5/2}$ proton state is completely emptied, it becomes near the $\nu p_{3/2}$, $\nu f_{7/2}$ states. Therefore, going from ^{30}Si to ^{24}O, the $N = 20$ shell gap gradually decreases, and $N = 14$, 16 shell gaps develop instead.

From systematic study of the neutron-rich oxygen isotopes the doubly closed nature of the $N = 14$ nucleus ^{22}O has been proven [4–7]; even the strength of the $N = 14$ shell closure was deduced to be 4.1 MeV [4]. Additionally, no bound excited states were observed in ^{23,24}O [4] nuclei, which is considered as a sign for the doubly closed character of the $N = 16$ nucleus ^{24}O, too. The presence of an $N = 16$ shell closure was deduced also from the systematics of the two neutron separation energies, as well as of the nuclear radii [8]. However, the strength of the $N = 16$ shell closure, which plays a crucial role in the determination of the dripline for the oxygen isotopes, has not been determined experimentally so far. The USD shell model calculation gives a size of 3.3 MeV for the $N = 16$ shell gap making ^{26,28}O bound by a few hundred keV [9,10]. However, if the $N = 16$ shell gap is a little larger (see the improved USD05 calculations in Refs. [11,12]), one can answer the long-standing question [13] why the oxygen isotopes heavier than ^{24}O become unbound while the fluorine isotopes are bound up to at least ^{29}F. For the strength of the $N = 20$ shell closure at $Z = 8$, there are different predictions in the *sdpf* model space ranging from 5.1 MeV [14] down to 1.5 MeV [15]. Up to now, there has been no experimental data accessible on the gap size, although the recent observation of a low-lying negative parity state intruding from above the $N = 20$ shell closure in ^{27}Ne [16–18] cannot be interpreted without a significant weakening of the $N = 20$ shell closure going from $Z = 20$ to 10.

Therefore, our aim was to determine the location of the excited states in ^{23}O which directly gives the single particle energies (since both ^{22}O and ^{24}O are proved to be doubly magic nuclei) suitable to deduce the size of the $N = 16$ and $N = 20$ shell closures. Single nucleon transfer reactions are ideal tools to map the location of these single particle states. The excited states of ^{23}O are suggested to be unbound [4]. A method often used with radioactive beams to study unbound nuclear states is the invariant mass spectroscopy that was first developed to study dripline nuclei via breakup reactions (see, e.g., Ref. [19]). As a new tool, to obtain information on single particle energies of unbound states next to the dripline, we applied the invariant mass spectroscopy combined with the (d, p) neutron transfer reaction.

The experiment was carried out at the accelerator research facility of the Institute of Physical and Chemical Research (RIKEN) where a 94 A MeV energy primary beam of ^{40}Ar with 60 pnA intensity hit a ^{9}Be production target of 3 mm thickness. The schematic view of the experimental setup is shown in Fig. 1. The reaction products were momentum- and mass analyzed by the RIKEN projectile fragment separator (RIPS) [20]. The secondary beam mainly included neutron-rich ^{25}Ne and ^{22}O nuclei. The RIPS was operated at 6% momentum acceptance. The total intensity was approximately 1500 cps having an average ^{22}O intensity of 600 cps. The identification of the incident beam species was performed by energy loss and time-of-flight (TOF). The separation of ^{22}O particles was complete. Two plastic scintillators of 1 mm thickness were placed at the first and second focal planes (F2 and F3) to measure the TOF. Silicon detectors with thickness of 0.5 mm were inserted at F2 and F3 for energy loss determination. The secondary beam was transmitted to a CD_2 target of 30 mg/cm^2 at the final focus of RIPS. The reaction occurred at an energy of 34 A MeV. The position of the incident particles was determined by two parallel plate avalanche counters placed at F3 upstream of the target. The scattered particles were detected and identified by a 2×2 matrix silicon telescope placed 96 cm downstream of the target. The telescope consisted of four layers with thicknesses of 0.5, 0.5, 2, and 2 mm. The first two layers were made of strip detectors (with 5 mm width of each strip) to measure the x and y positions of the fragments. On the basis of ΔE-E information, separation was carried out among the different oxygen isotopes using the linearized mass spectrum. The protons emitted backward in the reaction were detected by 156 CsI(Tl) scintillator crystals read out by photodiodes. The details of the CsI(Tl) ball and the particle identification quality is discussed in Ref. [21]; the γ rays and protons are well separated from each other down to 1–2 MeV energy of protons. A stack of 80 NaI(Tl) scintillator detectors (DALI2) [22] also surrounded the target to detect deexciting γ rays emitted by the inelastically scattered nuclei (for details see Ref. [7]). The neutrons coming from the decay of the produced ^{23}O nuclei excited above the neutron separation energy were detected by a neutron wall consisting of four layers of plastic scintillators placed at 2.5 m downstream of the target. Rods of two different lengths were used to build the wall: short neutron detectors with a dimension of 6 cm $\times$ 6 cm $\times$ 110 cm and long neutron detectors having the same section but 210 cm length. The energy of the neutrons was deduced from the TOF while the hit position was determined by identifying the rod that fired (in vertical direction) and by the time difference between the two photomultipliers attached to the ends of the rods (in horizontal direction). As a beam dump, plastic detectors of 0.5 cm and 1 cm thicknesses, used in veto mode, were placed in front of the neutron wall.

The excitation energy spectrum of ^{23}O shown in Fig. 2 was reconstructed from the momentum of the neutron and the heavy ion ^{22}O by calculating the invariant mass and using the known neutron separation energy (2.74 MeV).

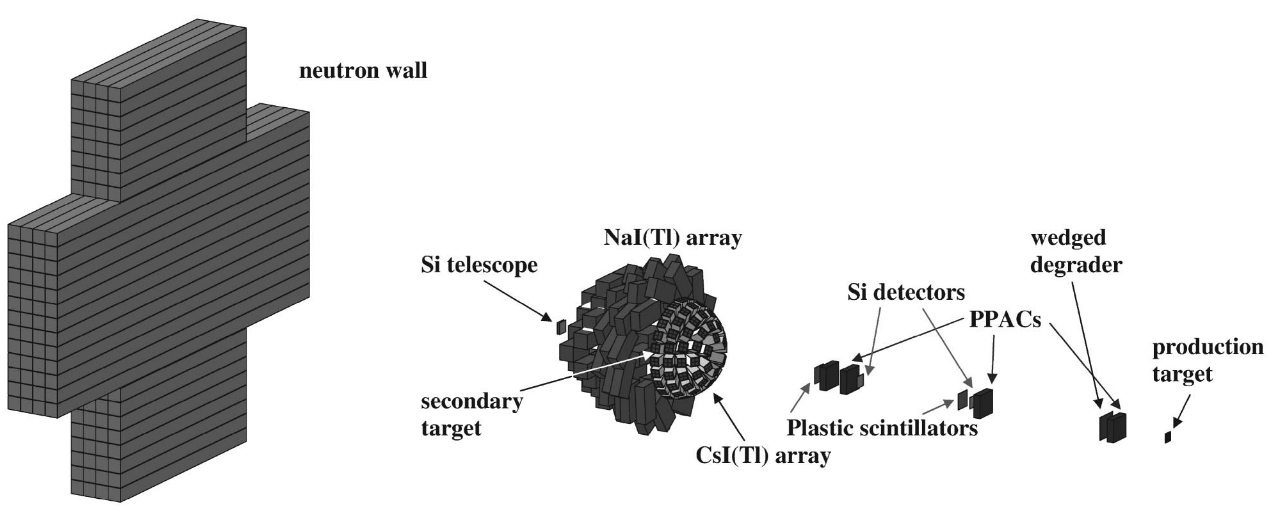

FIG. 1. Schematic view of the experimental setup (see text for details).

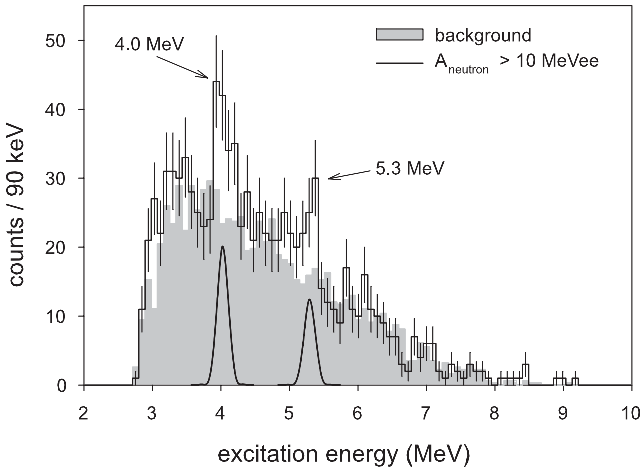

FIG. 2. Reconstructed excitation energy spectrum of ^{23}O. $A_{\rm neutron} > 10$ MeVee. Shaded spectrum represents the background (see text). In order to purify the spectrum, the neutron TOF was confined between 25 and 48 ns corresponding to a range of 13 MeV $< E_{\rm neutron} <$ 53 MeV.

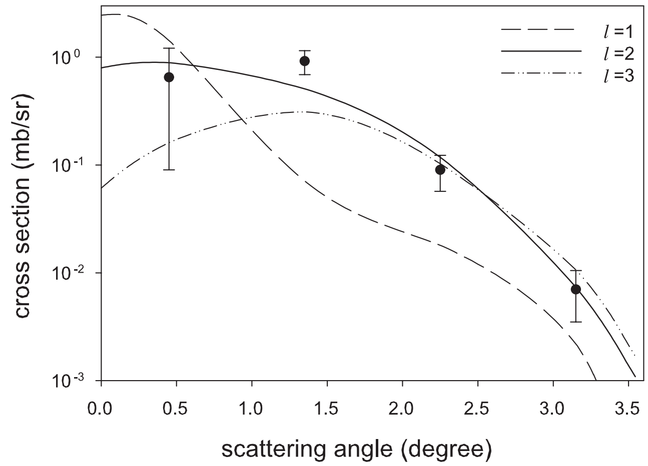

FIG. 3. Angular distribution for the 4 MeV inelastic channel of the ^{22}O$(d, p)^{23}$O reaction plotted together with the results of distorted wave calculations assuming different transferred angular momentum.

The zero point of the time spectrum was determined in a separate run by using the prompt γ rays emitted from a thick brass target. The neutron background mainly originates from reactions in the silicon telescope directly hit by the secondary beam. The shaded spectrum in Fig. 2 represents this background (downscaled) which was produced by using the same gate conditions but selecting background events in the linearized mass spectrum of oxygen isotopes. Two peaks are clearly visible at 4.00(2) MeV and 5.30(4) MeV in the spectrum produced by selecting neutrons with their light outputs (A) larger than 10 MeV of the electron-equivalent energy to cut the γ ray-induced events out. The spectrum was fitted by the convolution of the background spectrum and two Gaussian functions (plotted with thick solid lines in Fig. 2). The resolution of the peaks meets the expectations of ~200 keV FWHM deduced from the geometrical configuration of the detector system. GEANT4 [23] simulations were performed to determine the efficiency of the setup in order to deduce the total angle-integrated cross sections of the (d, p) reaction resulting in $\sigma(4.0\ \text{MeV}) = 0.84 \pm 0.17$ mb and $\sigma(5.3\ \text{MeV}) = 0.33 \pm 0.10$ mb taking into account the gates applied for the neutron TOF and energy (see the caption of Fig. 2). The distribution of the neutrons were assumed to be isotropic in center-of-mass system for the neutron decay of ^{23}O nuclei. The quoted errors represent only the statistical uncertainties in the spectra.

Furthermore, we could obtain the angular distribution for the 4 MeV inelastic channel (see Fig. 3) having 0.9° bin size on the scattering angle in order to provide information on the transferred angular momentum (ℓ). DWBA calculations were carried out with the code DWUCK [24] using optical potentials ^{16}O + d [25] for the entrance channel and ^{17}O + p [26] for the exit channel. These calculations suggest a d-wave nature of the state with spectroscopic factor $S_{\rm exp}(4\ \text{MeV}) = 0.5 \pm 0.1$ since the angular distribution could be fitted with this assumption resulting the smallest χ^2 value.

The (d, p) reaction populates the single particle states of ^{23}O. The ground state of this nucleus is experimentally determined to be the neutron $s_{1/2}$ state [27,28], while its first excited particlelike state is expected both by the sd [11,12] and the $sdpf$ [15] shell models to be the neutron unbound $d_{3/2}$ one shown in Fig. 4. [The $5/2^+$ state of the USD05 shell model at 2.75 MeV excitation energy in Fig. 4 is the neutron $d_{5/2}$ hole state hardly populated in the (d, p) reaction.] The experimental value for the energy of the first excited state, 4.0 MeV, is consistent with both shell model calculations. This results in a 4.0 MeV sized $N = 16$ shell gap at ^{23}O, which is large enough to make the ground state unbound in oxygen isotopes heavier than ^{24}O as it is shown by the USD05 calculations [11,12]. This finding explains why the oxygen isotopic chain is relatively short.

The next excited states of the USD05 shell model are at around 7.0 MeV [11,12]. Because of their spin and multiparticle character, these states are expected to have small spectroscopic factors. Thus, they can hardly correspond to our second excited state observed at 5.3 MeV populated with a relatively large cross section.

Extending the model space, the single particlelike states of the $sdpf$ shell model calculations with significant cross sections above the $d_{3/2}$ one are the $p_{3/2}$ (≈0.5 mb) and the $f_{7/2}$ (≈20 mb) states from the fp shell [15]. Taking into account the doubly closed nature of ^{22}O, the excitation of a single neutron to the fp shell should not cause a significant polarization effect. Therefore, if we consider that the experimental 5.3 MeV state corresponds to an intruder configuration from the fp shell, on the basis of the experimental cross section, it might correspond to the $\nu p_{3/2}$

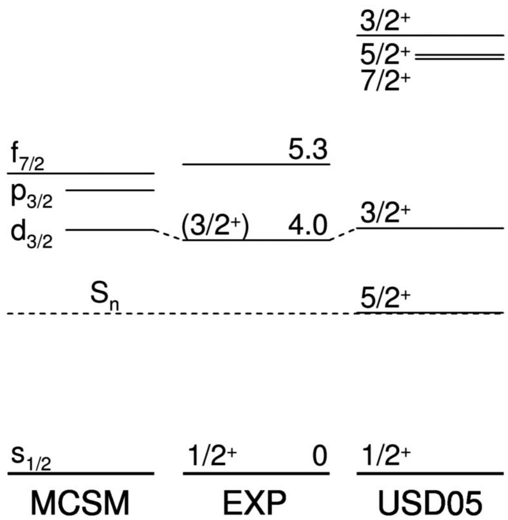

FIG. 4. Excited states of ^{23}O observed in the present experiment in comparison with the shell model calculation using the USD05 [11,12] interaction and the effective single particle energies taken from the Monte Carlo shell model (MCSM) calculation based on the SDPF-M interaction [15].

state with a relatively large spectroscopic factor [S_{exp}(5.3 MeV) $\approx$ 1.0]. Although, with smaller possibility, the $\nu f_{7/2}$ state assignment with very small spectroscopic factor [S_{exp}(5.3 MeV) $\approx$ 0.02] cannot be excluded. Furthermore, the observed relative energy of the two excited states (1.3 MeV) can be considered as the size of the $N = 20$ shell gap at $Z = 8$, which is in a good agreement with the Monte Carlo shell model value of ~1.5 MeV [15], and is quite different from other theoretical results (see, e.g., [14]) confirming a complete disappearance of this shell gap in oxygen isotopes. This observation together with the increased $N = 16$ shell gap basically corresponds with the qualitative predictions made using the tensor monopole interaction [3], which might give a possible explanation for the large change of the neutron single particle energies as a function of the proton number.

Summarizing our results, we have applied the method of the invariant mass spectroscopy in combination with the (d, p) reaction for the first time which enables us to study single particle properties of nuclei next to the neutron dripline. We investigated the excited states of ^{23}O observing two unbound nuclear states at 4.0 and 5.3 MeV energies. From a comparison with shell model calculations, the first one is the neutron $d_{3/2}$ state, the energy of which gives the $N = 16$ shell closure to be 4 MeV. This is large enough to explain why ^{24}O is the last bound oxygen isotope. The second excited state observed in the present experiment does not have any counterpart in the sd model space, and corresponds to a state from the fp shell. Its energy relative to the $d_{3/2}$ state determines the strength of the $N = 20$ shell closure to be 1.3 MeV and provides a direct evidence for the disappearance of the $N = 20$ shell closure at $Z = 8$.

We thank Dr. Y. Maeda for her help in preparing the CD_2 target. The present work was partly supported by the Grant-in-Aid for Scientific Research (No. 1520417) by the Ministry of Education, Culture, Sports, Science, and Technology and by OTKA No. T42733, No. T46901, and No. F60348.

[1] D. Warner, Nature (London) **430**, 517 (2004).
[2] J. Fridmann *et al.*, Nature (London) **435**, 922 (2005).
[3] T. Otsuka *et al.*, Phys. Rev. Lett. **87**, 082502 (2001).
[4] M. Stanoiu *et al.*, Phys. Rev. C **69**, 034312 (2004).
[5] P. Thirolf *et al.*, Phys. Lett. B **485**, 16 (2000).
[6] E. Becheva *et al.*, Phys. Rev. Lett. **96**, 012501 (2006).
[7] Z. Elekes *et al.*, Phys. Rev. C **74**, 017306 (2006).
[8] A. Ozawa *et al.*, Phys. Rev. Lett. **84**, 5493 (2000).
[9] www.nscl.msu.edu/~brown/resources/SDE.HTM
[10] E. K. Warburton and B. A. Brown, Phys. Rev. C **46**, 923 (1992).
[11] www.nscl.msu.edu/~brown/resources/usd-05ajpg/o_23.jpg
[12] B. A. Brown and W. A. Richter, Phys. Rev. C **74**, 034315 (2006).
[13] H. Sakurai *et al.*, Phys. Lett. B **448**, 180 (1999).
[14] E. K. Warburton, J. A. Becker, and B. A. Brown, Phys. Rev. C **41**, 1147 (1990).
[15] T. Otsuka *et al.*, Nucl. Phys. **A685**, 100 (2001).
[16] Z. Dombradi *et al.*, Phys. Rev. Lett. **96**, 182501 (2006).
[17] A. Obertelli *et al.*, Phys. Lett. B **633**, 33 (2006).
[18] J. Terry *et al.*, Phys. Lett. B **640**, 86 (2006).
[19] T. Motobayashi *et al.*, Phys. Lett. B **264**, 259 (1991).
[20] T. Kubo *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **70**, 309 (1992).
[21] Z. Elekes *et al.*, Eur. Phys. J. A **27**, 321 (2006).
[22] S. Takeuchi *et al.*, RIKEN Accel. Prog. Rep. **36**, 148 (2003).
[23] S. Agostinelli *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[24] P. Kunz, http://spot.colorado.edu/~kunz
[25] M. Cooper *et al.*, Nucl. Phys. **A218**, 249 (1974).
[26] G. Lerner and E. Redish, Nucl. Phys. **A193**, 565 (1972).
[27] D. Cortina-Gil *et al.*, Phys. Rev. Lett. **93**, 062501 (2004).
[28] C. Nociforo *et al.*, Phys. Lett. B **605**, 79 (2005).