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Role of multiparticle-multihole states in ^{18,19}O in thermal neutron capture of ^{18}O

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The primary $E1\gamma$-ray transition strength from the thermal neutron capture of ^{18}O to the $3/2^-$ state, 18 keV below the neutron threshold of ^{19}O, was found to be about 2×10^5 stronger than that to the $1/2^-$ excited state, 729 keV below the threshold. In addition, the $E1$ strength from the $3/2^-$ state leading to the $3/2^+$ state with three $(d_{5/2})^3$ neutrons was more than six times stronger compared to that to the $5/2^+$ ground state with a single $(d_{5/2})$ neutron. These anomalous γ-ray decay patterns give the first clear experimental evidence for the predicted property of the $3/2^-$ state as mainly having a one-hole-four-particle configuration. Unique features of the ^{18}O ground state with a two-hole-four-particle configuration and of the $3/2^+$ state combined with a discrete prompt γ-ray spectroscopy following the thermal neutron capture of ^{18}O enabled us to exclusively identify the configuration of the $3/2^-$ state.

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The low-energy neutron capture reaction of light nuclei from $A \sim 10$ to $A \sim 20$ has attracted considerable interest both in the study of the reaction mechanism [1–3] and the application of nuclear astrophysics [4–7]. A low-level density of excited states of light nuclei could allow us to observe a discrete γ-ray from neutron capture to low-lying states with well-known spin-parities in a neutron capture state. Since the electromagnetic multipolarity of a γ-ray is well-known, a discrete γ-ray carries important information on the nuclear structures and the reaction mechanism relevant to the neutron capture reaction. The detection of such a γ-ray from the neutron capture of light nuclei at thermal and keV neutron energies has been successfully carried out. In the latter case, a newly developed highly sensitive γ-ray detector [8,9] allowed us to detect discrete γ-rays from neutron capture by ^{12}C and ^{16}O, and find a new reaction process, as described below by referring to partial level schemes of ^{13}C and ^{17}O, shown in Figs. 1(a) and 1(b), respectively [5,7]. The thermal neutron captures of ^{12}C [10] and ^{16}O [11] are known to proceed via a non-resonant s-wave capture process, in which the $E1$ strength from the reaction leading to the $1/2^-$ state was very strong. On the other hand, the $E1$ strength from the reaction at keV energies leading to the $1/2^+$ state, known to be a weakly bound $s_{1/2}$ state with a large spectroscopic factor (C^2S), was found to be much stronger than that to the $1/2^-$ state [5–7]. This observation together with a smooth increase of the partial cross section for the $E1\gamma$-ray with increasing incident neutron energy was successfully interpreted in terms of a non-resonant direct p-wave capture process [6,12,13], in which the matrix element for $E1\gamma$-ray transition for incident p-wave neutron capture, leading to the loosely bound $\ell = 0(s_{1/2})$ state, was shown to be quite large.

Similarly, the nuclear properties of low-lying states of ^{19}O, shown in Fig. 1(c), have been extensively studied by the ^{17}O$(t, p)^{19}$O and ^{18}O$(d, p)^{19}$O reactions [14–16] and the magnetic moment measurement for the $5/2^+$ground [17] and $3/2^+$first excited [18] states. In fact, the $1/2^+$and $5/2^+$states, lying at 2.5 and 4 MeV below the neutron threshold of ^{19}O, respectively, are considered to be the $s_{1/2}$ and $d_{5/2}$ neutron states with spectroscopic factors (C^2S) of 1.0 and 0.57, respectively, similarly to the cases for ^{13}C and ^{17}O. Contrary to the cases for ^{13}C and ^{17}O, two negative parity states of $3/2^-$ and $1/2^-$ exist ~ 20 keV and 700 keV below the neutron threshold of ^{19}O, respectively, which could be compared to 5 MeV of the $1/2^-$ state of ^{13}C. In addition, a quite unique state, the $3/2^+$ state with a three-particle $(d_{5/2})^3$ configuration with a $C^2S = 0.013$ [14–16], exits only in ^{19}O at $E_x = 0.096$ MeV. The measured magnetic moment of the $3/2^+$ state is consistent with the value expected for the $(d_{5/2})^3$ neutron [18]. However, the ground state of ^{18}O is known to contain two-neutron shell-model states, multiparticle-multihole states, and states with a cluster structure, based on detailed studies using such reactions as ^{16}O$(t, p)^{18}$O, ^{17}O$(d, p)^{18}$O, ^{14}C$(\alpha, \gamma)^{18}$O, and ^{18}O$(e, e')^{18}$O [19–23]. Many theoretical studies of the nuclear properties of ^{18}O and ^{19}O have also been carried out [24–27]. Note that Warburton predicted a one-hole four-particle (1h-4p) negative-parity state near the neutron threshold of ^{19}O, which remains to be studied experimentally [27].

These unique structures of ^{18}O and^{19}O make the study of thermal neutron capture of ^{18}O very attractive. Experimentally, the total reaction cross section was measured by an activation method [28]. The first successful measurement of discrete γ-rays from the reaction were made by Ohsaki *et al.* by means of a Ge detector using thermal neutrons at Kyoto University Research Reactor Institute [29]. By analyzing observed discrete γ-rays, they claimed the neutron separation energy of ^{19}O to be larger than a previous value by about 7 keV. This finding prompted us to reinvestigate the reaction using a high neutron flux and a highly sensitive γ-ray detector to improve both the statistics and the signal-to-noise ratio of

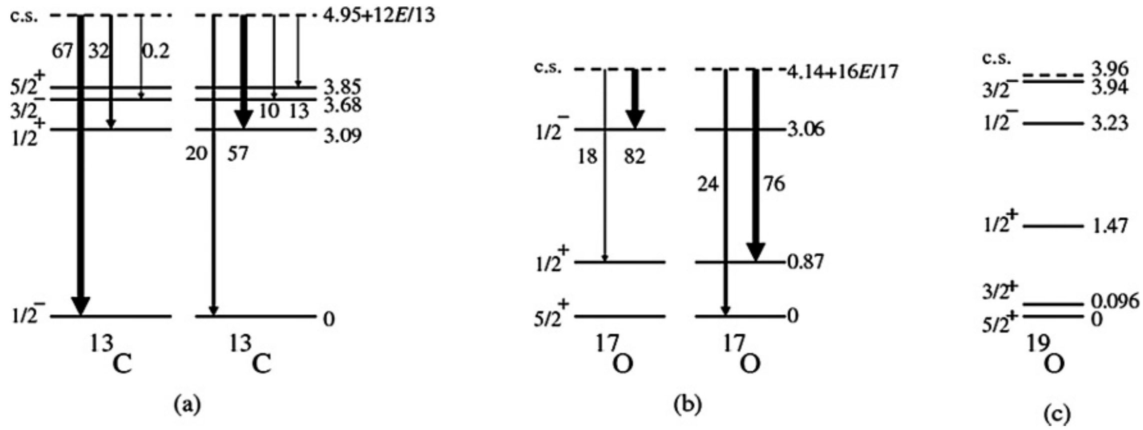

FIG. 1. Partial level schemes of ^{13}C (a), ^{17}O (b), and ^{19}O (c) are shown. The relative γ-ray intensities obtained from the thermal and fast (keV) neutron capture reactions of ^{12}C and ^{16}O are also shown in the left and right sides of (a) and (b), respectively. E is incident neutron energy.

the measured γ-ray spectrum, and to learn about any role of the mentioned 2h-4p configuration of ^{18}O and of the $3/2^+$ three-particle $(d_{5/2})^3$ state in the reaction.

The experiment was carried out at the thermal neutron beam port at the nuclear reactor, JRR-3, at Japan Atomic Energy Agency [30]. Prompt discrete γ-rays from ^{18}O$(n,\gamma)^{19}$O to low-lying states in ^{19}O were detected by means of an anti-Compton Ge spectrometer [31]. The spectrometer consisted of a HPGe detector with a diameter of 51 mm and a length of 52.7 mm, and a BGO detector with an outer-diameter of 171 mm and a length of 206 mm. A $D_2\,^{18}O$ sample of 12.9 g with 95.1% enriched in ^{18}O and 98.5% enriched in D_2, and a natural $D_2^{nat}O$ sample of 12 g were used to obtain a background-free γ-ray spectrum from ^{18}O$(n,\gamma)^{19}$O. We used a $D_2\,^{18}O$ sample instead of a $H_2\,^{18}O$ sample to measure the γ-ray spectrum with a good signal-to-noise ratio, since the measured total thermal neutron capture cross section of ^{18}O is as small as 0.2 mb. The cross section of ^{2}H$(n,\gamma)^3$H for thermal is quite small, one thousandth of that for hydrogen. These samples were contained in a cylindrical case, made of Lucite. The detection efficiency of the Ge detector was determined by using standard γ-ray sources, such as ^{56}Co and ^{66}Ga, and γ-rays from the ^{35}Cl$(n,\gamma)^{36}$Cl reaction [32]. The γ-ray events from the thermal neutron capture by the samples were stored on a hard disk of a personal computer.

Discrete γ-rays from neutron capture by $D_2\,^{18}O$ (solid line) and $D_2^{nat}O$ (dotted line) samples were measured with a good signal-to-noise ratio, as shown in Fig. 2. In the background spectrum from the $D_2^{nat}O$ sample, we observed the 197 and 1356 keV γ-rays from the β-decay of ^{19}O to ^{19}F with a half-life of 26.9 s, and γ-rays from the (n,γ) reaction by H, ^{7}Li, ^{10}B, ^{12}C, ^{19}F, ^{73}Ge, and ^{56}Fe, and from the β-decays of ^{40}K and ^{235}U. Background-subtracted (net) spectra were obtained as shown in Fig. 3(a)–3(h) by subtracting the spectrum of $D_2^{nat}O$ from that of $D_2\,^{18}O$, where the normalization of two spectra was made by referring to the 6257 keV γ-ray yield from ^{2}H$(n,\gamma)^3$H by $D_2\,^{18}O$ to that by $D_2^{nat}O$. Consequently, we could clearly identify seven discrete γ-rays from ^{18}O$(n,\gamma)^{19}$O, as listed in Table I together with the relative intensities of observed γ-rays, I_γ, and the partial capture cross sections for the transitions leading to the $3/2^-$, $1/2^-$, and $1/2^+$ states.

Among seven observed γ-rays, five discrete γ-rays of $96.0(3/2^+ \to 5/2^+)$, $1375.0(1/2^+ \to 3/2^+)$, $2473.0(3/2^- \to 1/2^+)$, $3137.3(1/2^- \to 3/2^+)$, and 3848.0 $(3/2^- \to 3/2^+)$ keV, could be successfully placed as

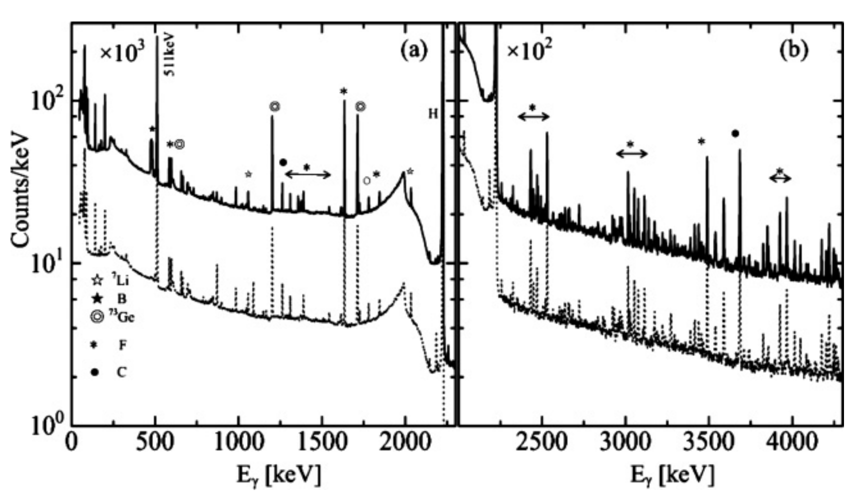

FIG. 2. γ-ray spectra of thermal neutron capture of enriched ^{18}O $D_2\,^{18}O$ (solid line) and natural O $D_2^{nat}O$ (dotted line) samples are shown. Background γ-rays from thermal neutron capture by ^{7}Li (☆), ^{10}B (⋆), ^{12}C (•), ^{19}F (∗), and ^{73}Ge (◎) are observed.

TABLE I. Relative intensities, I_γ, of observed γ-rays with energy E_γ (in units of keV) normalized to the 1375 keV transition from $1/2^+ \rightarrow 3/2^+$, and measured partial capture cross sections, σ_γ (in units of μb), are given. The 18.4 and 3944 keV γ-rays in curly brackets were not observed.

E_γ(keV)	Placement	I_γ	$\sigma_\gamma(\mu\text{b})$	E_γ(keV)	Placement	I_γ	$\sigma_\gamma(\mu\text{b})$
(18.4)	$c.s. \rightarrow 3944$	123(10)	100(10)	3137.3(5)	$3233 \rightarrow 96$	31(4)	
96.0(5)	$96 \rightarrow 0$	198(30)		3848.0(5)	$3944 \rightarrow 96$	66(7)	
729.4(5)	$c.s. \rightarrow 3233$	36(5)	32(5)	3944	$3944 \rightarrow 0$	<11	
1375.0(5)	$1471 \rightarrow 96$	100					
2473.0(5)	$3944 \rightarrow 1471$	46(6)		197.3(5)	$190 \rightarrow 19F$	197(16)	166(13)
2491.4(5)	$c.s. \rightarrow 1471$	31(4)	28(4)	1356.5(5)	$190 \rightarrow 19F$	101(9)	85(8)

the γ-ray transitions connecting between the bound states in ^{19}O [see Fig. 1(c)]. However, two γ-rays of 729.4, and 2491.4 keV remain to be placed in the level scheme. In addition, we have the following problems. First, we could not identify any γ-ray transitions from $^{18}\text{O}(n,\gamma)^{19}\text{O}$ to low-lying states of ^{19}O when we used the reaction Q-value for the thermal neutron capture of ^{18}O, $S_n(^{19}\text{O})$, 3955.7 keV, as reported in Ref. [33]. Second, we could not place any γ-ray transitions from a higher lying excited state to the

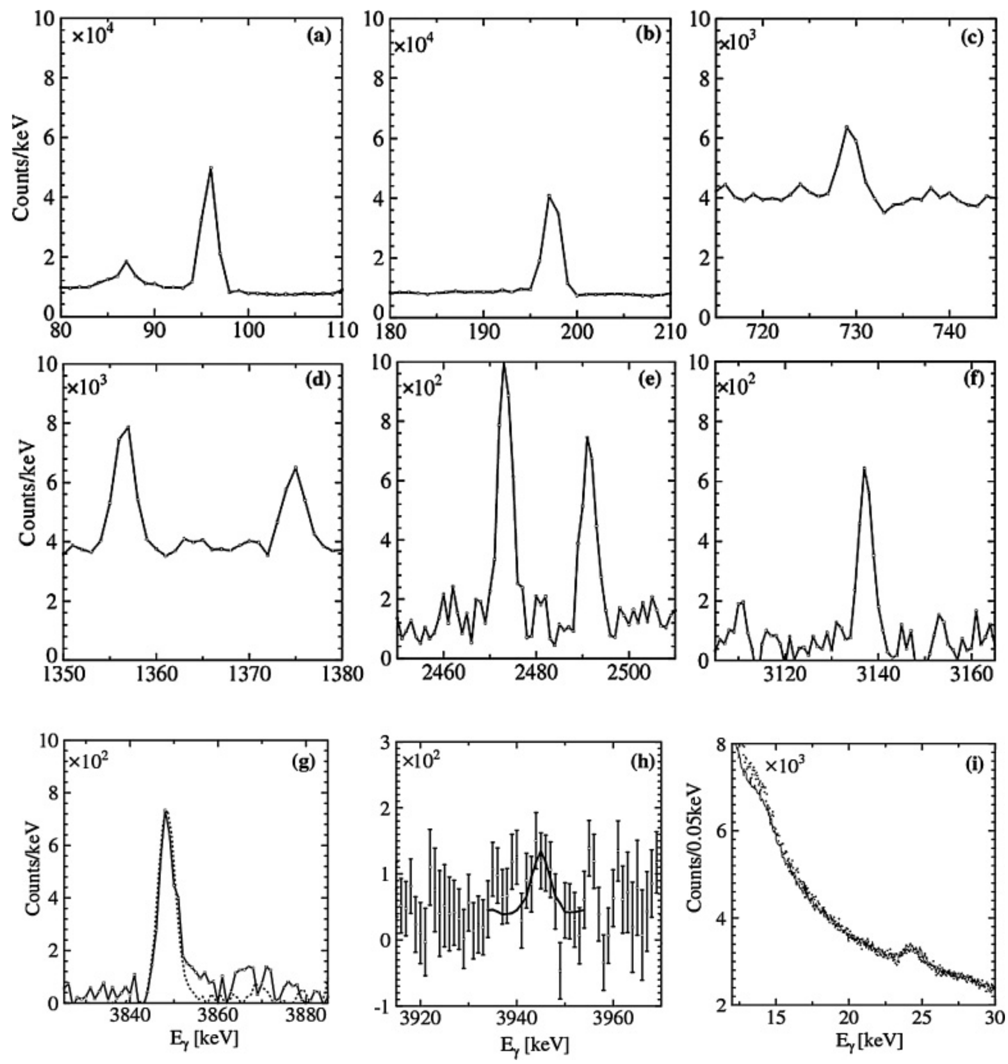

FIG. 3. Background subtracted (net) partial γ-ray spectra of thermal neutron capture of $D_2\,^{18}O$ sample (solid line) are shown. (g) The dotted curve shows the fitted curve by using the experimental response function of the Ge spectrometer. (h) The 3944 keV γ-ray peak was not clearly observed in the net spectrum (circle with an error bar). The solid line shows the fitted curve to determine the maximum yield of the 3944 keV γ-ray. (i) γ-ray energy spectra collected using the enriched $D_2\,^{18}O$ sample (solid curve) and the natural D_2O sample (dotted curve) in the region of 18 keV. We could not observe the 18 keV γ-ray from $^{18}\text{O}(n,\gamma)^{19}\text{O}$ to the $3/2^-$ state.

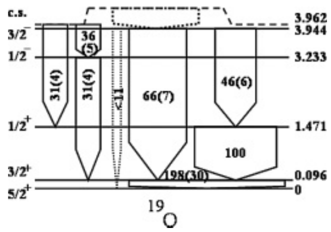

FIG. 4. A newly proposed partial level scheme of ^{19}O is shown. The observed γ-rays from thermal neutron capture by ^{18}O are given. The widths of the lines with the numbers show the relative γ-ray strengths of the transitions normalized to the 1375 keV transition from $1/2^+ \to 3/2^+$. The γ-rays (dotted lines) from ^{18}O$(n,\gamma)^{19}$O $\to 3/2^-$ and from $3/2^- \to 5/2^+$ were not observed.

$1/2^-$ state, although we observed the 3137.3 keV γ-ray transition from $1/2^- \to 3/2^+$. Third, we observed the γ-ray transition strength from $1/2^+ \to 3/2^+$ to be stronger than that from $3/2^- \to 1/2^+$. There must be γ-ray transitions from high-lying states to the $1/2^+$ state.

The problems mentioned could be solved if $S_n(^{19}\mathrm{O})$ would be 3962.4±1 keV, as claimed in Ref. [29], but not 3955.7 keV. In fact, the 2491.4 and 729.4 keV γ-rays were placed in a newly constructed level scheme as the transitions from a neutron capture state of ^{18}O to the $3/2^+$, $1/2^+$, and $1/2^-$ states, respectively, as shown in Fig. 4. The new placement of three γ-rays could also solve the above-mentioned problems of intensity imbalance, as described below. The change of $S_n(^{19}\mathrm{O})$ from 3957 to 3962.4 keV is allowed within the reported experimental uncertainty of ~8 keV [33]. The $S_n(^{19}\mathrm{O})$ of 3955.7 keV was determined by deriving the mass of ^{19}O using the mass of ^{18}O and the measured Q-value of the ^{18}O$(d,p)^{19}$O reaction [33]. Note that we could not observe the 18 keV γ-ray from ^{18}O$(n,\gamma)^{19}$O to the $3/2^-$ state due to a large Compton tail due to high-energy γ-rays from the reaction, and due to γ-ray attenuation by 1 cm thick LiF, placed in front of the Ge detector to shield it against neutrons scattered by a sample [see Fig. 3(i)].

The level scheme of ^{19}O deduced from the present work is given in Table II, where I_γ with energy E_γ, and a total γ-ray intensity flowing into $\sum I_\gamma$(in) and/or flowing out $\sum I_\gamma$(out) of a level at energy E_x are given. A total γ-ray intensity flowing into an each level agrees nicely with that flowing out of the level, indicating that all of the observed γ-rays are properly placed in the new level scheme. It should also be mentioned that the total neutron capture cross section was derived as 160 ± 10 μb by normalizing the 1356 keV γ-ray yield from the β-decay of ^{19}O with the 1088 keV γ-ray yield of the ^{16}O$(n,\gamma)^{17}$O reaction with the well known $\sigma_{16O}(n,\gamma)$ of 187 ± 10 μb [34], it agrees with an old value of 160 ± 10 μb [35].

The present data reveal very interesting features of the nuclear structures and reaction mechanism, as described below. First, an incident s-wave neutron was dominantly captured into the $3/2^-$ sub threshold state, 18 keV below the neutron threshold of ^{19}O, compared to capture into the $1/2^-$ state, 729 keV below the threshold. The reduced γ-ray strength to the former is about two hundred thousand times stronger than the latter. Second, the $E1\gamma$-ray transition intensities for $3/2^- \to 3/2^+$ and $3/2^- \to 1/2^+$ are very strong, but the intensity for $3/2^- \to 5/2^+$ was quite weak, less than one-sixth of that for $3/2^- \to 3/2^+$. Similarly, an $E1\gamma$-ray transition for $1/2^- \to 3/2^+$ was clearly observed. These characteristic features of γ-ray decays can be understood by considering the unique configurations of the ^{18}O ground state with two-hole four-particle (2h-4p) and of the $3/2^+$ with the $(d_{3/2})^3$ neutrons, as described below.

The wave functions of the relevant states may be expressed using numerical coefficients, $a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, p, q$, and r, that determine the amount of each wave function in each nuclear state. The ground state of ^{18}O is considered to consist mainly of two neutrons outside the core of ^{16}O and of a 5–10% 2h-4p component [25,26], as given in

$$|0^+\rangle = a\big|(s\,d)^2_{J=0}\big\rangle + b\big|(p)^{-2}_{J=0}(s\,d)^4_{J=0}\big\rangle + c\big|(p)^{-2}_{J=2}(s\,d)^4_{J=2}\big\rangle. \quad (1)$$

Here, s, p, and d stand for the s-, p-, and d-shell, respectively. The symbol J is the total angular momentum of the neutrons in the p- and/or sd-shells. A non-resonant direct s-wave neutron capture by ^{18}O leads to the following configurations as a scattering state:

$$|\text{scat state.}\rangle = d\big|n\otimes(s\,d)^2_{J=0}\big\rangle + e\big|n\otimes(p)^{-2}_{J=0}(s\,d)^4_{J=0}\big\rangle + f\big|n\otimes(p)^{-2}_{J=2}(s\,d)^4_{J=2}\big\rangle. \quad (2)$$

Here, the second and third states are 2h-5p states with $2\hbar\omega$ excitation with respect to low-lying positive-parity states of ^{19}O. The $1/2^+, 3/2^+$, and $5/2^+$ states in ^{19}O can be

TABLE II. Level scheme of ^{19}O determined from the present work.

E_x (keV)	J^π	Deexcitingγ-rays	$\sum I_\gamma$(in)	$\sum I_\gamma$(out)	$\sum I_\gamma$(in-out)
0.0	$5/2^+$		209(30)	205(17)[a]	4(34)
96.0(5)	$3/2^+$	96.0	197(8)	198(30)	−1(31)
1471.0(5)	$1/2^+$	1375.0	77(7)	100	−23(7)
3233.3(5)	$1/2^-$	3137.3	36(5)	31(4)	5(6)
3944.0(5)	$3/2^-$	3848.0, 2473.0	112(9)	112(9)	0(13)
3962.4(5)	$1/2^+$	2491.4, 729.4			
		18.4[b]		179(11)	−179(11)

[a]Derived using the I_γ for the known 197.3 keV γ-ray from ^{19}O $\to$ ^{19}F.

[b]Unobserved because of the large background at low γ-ray energies and the 1 cm thick LiH.

described as follows, based on the arguments mentioned above:

$$|1/2^+\rangle = g\left|(s_{1/2})^1\,(d_{5/2})^2_{J=0}\right\rangle + h\left|(d_{3/2})^1\,(d_{5/2})^2_{J=2}\right\rangle, \quad (3)$$

$$|3/2^+\rangle = j\left|(d_{5/2})^3_{J=3/2}\right\rangle + k\left|(s_{1/2})^1(d_{5/2})^2_{J=2}\right\rangle, \quad (4)$$

and

$$|5/2^+\rangle = l\left|(d_{5/2})^3_{J=5/2}\right\rangle. \quad (5)$$

The negative parity states were calculated by using a modification of the Millener-Kurath interaction [27] and/or the WBN interaction of Warburton and Brown [28], and the thus obtained wave functions are 4p-1h excitations mostly from the full p into the sd shell [28]. Hence, similarly to the case mentioned above, the $3/2^-$ state could be described, as

$$|3/2^-\rangle = m\left|(p_{3/2})^1(s\,d)^2_{J=0}\right\rangle + n\left|(p_{3/2})^{-1}(s\,d)^4_{J=0}\right\rangle + o\left|(p_{1/2})^{-1}(s\,d)^4_{J=2}\right\rangle. \quad (6)$$

In the present study, an $E1\gamma$-transition from the $3/2^-$ state was observed to strongly feed the $3/2^+$ state with the three $(d_{5/2})^3$ neutrons, but weakly the $5/2^+$ state with the single $(d_{5/2})$ neutron. Hence, the third term in Eq. (6) with the one-hole four-particle configuration having three unpaired particles, seniority three ($v = 3$), would contribute mostly to reach the $3/2^+$ state through a single-particle transition, $d_{5/2} \to p_{3/2}$. An observed weak $E1\gamma$-transition from the $3/2^-$ state to the $5/2^+$ state indicates the coefficients m and n in Eq. (6) to be small. It should be noted that the former two terms in Eq. (6) cannot contribute to reach the $3/2^+$ state via an $E1\gamma$-transition, since two and four neutrons in the sd-shell have seniority $v = 0$, and the single-particle transitions $d_{5/2} \to \mathrm{p}_{3/2}$ and $s_{1/2} \to \mathrm{p}_{3/2}$ of the $E1$ decay can not leave the $v = 3$ component in the sd-shell. The $3/2^-$ state with $v = 3$ could be populated by an s-wave capture of ^{18}O with the two-hole four-particle states of ^{18}O with $v = 2$ in Eq. (2). Here, it should be mentioned that the $3/2^-$ state was predicted to be one-hole four-particle states by Warburton [27] about two decades ago, but the prediction has not yet been proven experimentally. In fact, the $3/2^-$ state, having a small spectroscopic factor 0.1 in the previous studies of the ^{18}O$(d, p)^{19}$O reaction, deserved further study [15]. The present result gives for the first time clear evidence of the prediction.

Similarly, the $1/2^-$ state is described as

$$|1/2^-\rangle = p\left|(p_{1/2})^1(s\,d)^2_{J=0}\right\rangle + q\left|(p_{1/2})^{-1}(s\,d)^4_{J=0}\right\rangle + r\left|(p_{3/2})^{-1}(s\,d)^4_{J=2}\right\rangle. \quad (7)$$

Since we observed $E1\gamma$-transitions for $1/2^- \to 3/2^+$, and for a neutron capture state of $^{18}\mathrm{O} \to 1/2^-$, the third term with $v = 3$ in Eq. (7) would also contribute to reach the $3/2^+$ state with $v = 3$ from the $1/2^-$ state. Similarly to the case mentioned for the $3/2^-$ state, the two-hole four-particle states of ^{18}O of $v = 2$ in Eq. (2) contribute to populate the $1/2^-$ state with $v = 3$. Here, it should be mentioned that we obtained partial capture cross sections for the transition leading to the $3/2^-$ and $1/2^-$ states (Table I), and we know well the properties of the 2h-4p configurations of the ground state of ^{18}O and of the $3/2^+$ state of ^{19}O. Hence, one can calculate the coefficients of the $3/2^-$ and $1/2^-$ states. The problem, however, is beyond the present study.

We also observed an intense $E1\gamma$-transition from the $3/2^-$ to the $1/2^+$ states. If the $1/2^+$ state is dominated by the $s_{1/2}$ neutron, the $1/2^+$ state can not be reached by an $E1\gamma$-transition, since the 1h-4p $3/2^-$ state with $v = 3$ cannot reach the one neutron state in the $s_{1/2}$ shell. Hence, the $1/2^+$ state should also have the three-particle neutron component, as described in Eq. (3). The characteristic structure of the $1/2^+$ state having a dominant $s_{1/2}$ component together with the three neutron component could be a possible reason of the poor agreement of the angular distribution observed in the ^{17}O$(t, p)^{19}$O reaction with a theoretical calculation [14–16]. A detailed study of the problem is beyond the present study.

In conclusion, we have measured discrete γ-rays from thermal neutron capture of ^{18}O using a highly sensitive anti-Compton Ge detector with a good signal-to-noise ratio. The neutron separation energy of ^{19}O was found to be 3962.4 keV, 5.4 keV higher than a previous value, as proposed in Ref. [29]. We could clearly identify for the first time the $3/2^-$ state of ^{19}O at 3944 keV to have one-hole four-particle component, which remained as a long-standing problem. It should be stressed that unique nuclear structures of ^{18}O containing a certain amount of the two-hole four-particle component and of the $3/2^+$ three-particle $(d_{5/2})^3$ state together with a well-known $E1$ property of the observed γ-rays in the s-wave thermal neutron capture of ^{18}O played an essential role in identifying the predicted 1h-4p state.

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