De-excitation $\gamma$-rays from the $s$-hole state in $^{15}\text{N}$ associated with proton decay in $^{16}\text{O}$

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We have measured de-excitation $\gamma$-rays from the $s$-hole state in $^{15}\text{N}$ produced via the $^{16}\text{O}(p, 2p)^{15}\text{N}$ reaction in relation to the study of the nucleon decay and the neutrino neutral-current interaction in water Cherenkov detectors. In the excitation-energy region of the $s$-hole state between 16 MeV and 40 MeV in $^{15}\text{N}$, the branching ratio of emitting $\gamma$-rays with the energies at more-than-6 MeV are found to be $15.6\pm1.3^{+0.6}_{-1.0}\%$. Taking into account the spectroscopic factor of the $s$-hole state, the total emission probability is found to be 3.1%. This is about 1/10 compared with the emission probability of the 6.32 MeV $\gamma$-ray from the $3/2^{-}\rightarrow 1/2^{+}$ state which may be populated after the particle-decay of the $s$-hole state in $^{15}\text{N}$. Such a high energy $\gamma$-ray from the hole state would provide a new method to search for mode-independent nucleon decay even if the emission probability is small. No significant signal is found within a statistical uncertainty.

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I. INTRODUCTION

In the recent searches of proton decay and in the studies of neutrino oscillations, water Cherenkov detectors are used, such as Super-Kamiokande. Since in such detectors, proton decays or neutrino interactions happen mostly in $^{16}\text{O}$, it is important to study the effect of the nuclear de-excitation process on the Cherenkov light detection in more detail.

When a proton decays in one of the inner-shell orbits of $^{16}\text{O}$, the residual $^{15}\text{N}$ nucleus remains in an excited state with a proton-hole. This state quickly de-excites by emitting $\gamma$-rays with a certain probability. In the decay search involving the channel $p \rightarrow \bar{\nu}K^{+}$, which is the dominant process in many supersymmetric grand unification models, the de-excitation $\gamma$-rays would be very useful to reduce backgrounds. Since the $K^{+}$ momentum is below the Cherenkov threshold, the $K^{+}$ signal can be separated from the prompt $\gamma$-ray signal. On the other hand, most backgrounds produced by events such as $\nu N \rightarrow \mu N$ have no time difference between the $\gamma$-ray and $\mu$ signals and can be eliminated when the $\gamma$-ray energy ($E_{\gamma}$) is in the detectable energy range of the Super-Kamiokande.

The de-excitation $\gamma$-ray is also useful for the study of the neutrino neutral-current interaction via the quasi-free knock-out process, e.g. with a 1 kt water Cherenkov detector in the experiment of the long base-line neutrino oscillation from KEK to Super-Kamiokande (K2K).
An overall neutrino flux independent of neutrino flavor can be estimated from the measurement of the neutral-current interaction. Because recoil energies of protons are mostly below the Cherenkov threshold, Cherenkov light from the de-excitation $\gamma$-rays can be clearly observed. It is then possible to tag the neutral-current interaction with the $\gamma$-rays.

The de-excitation process of hole states in $^{15}$N following proton decay in $^{16}$O was discussed by Ejiri \[9\]. He summarized de-excitation modes and their branching ratios, and estimated the emission probabilities of the de-excitation $\gamma$-rays. For a hole state $k$ which de-excites only by $\gamma$ decay, he estimated the $\gamma$-ray emission probability ($P(k)$) by using the spectroscopic factor ($S_p(k)$) as $P(k) = S_p(k)/8$, where 8 is the number of protons in $^{16}$O. The 6.32 MeV $\gamma$-ray from the 3/2$^-$ p-hole state to the ground state (g.s.) in $^{15}$N, which is in the detectable energy range of the Super-Kamiokande detector, is the most probable one because the state has the largest spectroscopic factor and its excitation energy is below the particle emission threshold. Using the spectroscopic factor from the $(d,^3$He) data \[10\] (see Table II), Ejiri predicted that the emission probability of the 6.32 MeV $\gamma$-ray is $41\%$ ($P(6.32$ MeV p$_{3/2^-} = S_p(6.32$ MeV p$_{3/2^-})/8 = 3.3/8$). He also estimated the $\gamma$-ray emission probabilities from other p-hole and s-hole states to be several percent, respectively. However, the emission probabilities from the s-hole state around 25 MeV excitation are uncertain. The s-hole state de-excites mostly by particle emissions, because the excitation energy exceeds the particle emission threshold (10.21 MeV for proton decay and 10.83 MeV for neutron decay). If the residual nucleus remains in an excited state, secondary $\gamma$-rays are emitted. Ejiri statistically evaluated the emission probabilities by $P(k) = S_p(s$-state)/$8 \times S_p(k)/N_p \times b(N)$, where $S_p(k)$ is the spectroscopic factor of the excited state $k$ in the daughter nucleus, $N_p (= 11)$ is the number of p-shell nucleons in $^{15}$N, and $b(N)$ is the escape ratio of the nucleon. The excited states most likely to be populated were the 7.01 MeV 2$^+$ state in $^{14}$C and the 7.03 MeV 2$^+$ state in $^{14}$N each with $P(k) = 2\%$.

However, a recent study \[11\] showed that the particle-decay data of deep-hole states in light nuclei cannot be reproduced in a statistical-model calculation. The probability to remain the secondary excited states after particle emissions of the s-hole state in $^{15}$N was found to be high. The results suggested that the direct two-body decay process from the door-way s-hole state predicted by the theoretical calculations based on a SU(3)-model \[12\] and a shell model \[13\] considerably occurred. Thus, from a nuclear-structure point of view, it is also interesting to measure such secondary de-excitation $\gamma$-rays.

After the work by Ejiri \[9\], the spectroscopic factors of p-hole state have been investigated in an $^{16}$O(e,$e'$p)$^{15}$N experiment \[14\]. The result suggests that the spectroscopic factors in the p-shell orbits are substantially lower than the sum-rule limit ($S_p(p_{3/2}) = 4$) in the independent-particle shell-model; the spectroscopic factor of the 6.32 MeV p-state is smaller than that given by Ref. \[9\] by 30% as shown in Table II. The difference is mainly due to a large theoretical uncertainty associated with the reaction mechanism. The spectroscopic factor derived from transfer reactions strongly depends on the delicate details of the distorted wave Born approximation \[15\]. This result indicates that the direct measurement of $\gamma$-rays from the s-hole state is important.

The nucleon-hole state is created via any modes of nucleon decay. The de-excitation $\gamma$-ray is a mode-independent signal of the nucleon decay. If the decay particles do not emit Cherenkov light (for example in $n \rightarrow \nu\nu\bar{\nu}$ decay), the only detectable signal is Cherenkov light from the $\gamma$-ray. Since in the energy region below 10 MeV the signal in the Super-Kamiokande is contaminated by strong backgrounds from radioactivities, $\gamma$-rays with $E_\gamma > 10$ MeV are useful to tag the nucleon decay. Though the energies of most $\gamma$-rays from the s-hole state in $^{15}$N are expected to be less than 10 MeV, two different $\gamma$-rays over 10 MeV can be emitted. One is the direct $\gamma$-ray with $E_\gamma = 20$–30 MeV from the unbound s-hole state. However, it was estimated that the emission probability is quite small \[16\]. The other is a unique 15.1 MeV $\gamma$-ray which can be emitted mainly from the $T=1$ 1$^+$ state in $^{12}$C after $t$ decay, $n+d$ decay, or $2n+p$ decay from the s-hole state in $^{15}$N. This $\gamma$-ray is useful to tag the mode-independent nucleon decay with small backgrounds in Super-Kamiokande.

In this paper, we present the first measurement of the de-excitation $\gamma$-rays with $E_\gamma < 18$ MeV from the s-hole state in $^{15}$N produced via the $^{16}$O(p,2p)$^{15}$N reaction. These $\gamma$-rays are useful for the proton decay search and the study of neutrino neutral-current interaction. Especially, in the dominant method of proton decay search via $p \rightarrow \bar{\nu}K^+$ in Super-Kamiokande, the partial lifetime of proton is estimated to be proportional to the emission probability of the de-excitation $\gamma$-ray. Therefore, this measurement is important to obtain the precise emission probability. It is also important for determining the proton decay sensitivity in future experiments \[17\], \[18\]. In terms of the 15.1 MeV $\gamma$-ray from the $^{12}$C 1$^+$ state, even if the emission probability of this $\gamma$-ray is down to 0.01%, it would provide a new method to search for mode-independent nucleon decay above the current decay limit obtained by SNO \[19\]. Because the proton s-hole

### Table I: Comparison of spectroscopic factors of the dominant p-hole states in $^{15}$N.

| Energy (MeV) | J$^+$ | Ref. \[9\] | Ref. \[14\] |
|-------------|------|----------|----------|
| 0           | 1/2  | 2        | 1.26     |
| 5.27        | 5/2$^+$ | —   | 0.11     |
| 6.32        | 3/2$^-$ | 3.3   | 2.35     |
| 9.93        | 3/2$^-$ | 0.26   | 0.13     |
state in $^{15}$N and neutron s-hole state in $^{15}$O are isospin-symmetric, the $^{12}$C $^{1+}$ state is expected to be produced similarly. The present measurement is also useful for neutron decay search, such as $n \to \nu \nu \bar{\nu}$ mode.

II. EXPERIMENT

The experiment was carried out at the Research Center for Nuclear Physics (RCNP), Osaka University using 392 MeV proton beam from the cyclotron facility. The proton beam impinged on a H$_2$O ice target in order to generate the $^{16}$O($p, 2p$)$^{15}$N reaction. Two protons were detected in coincidence in the dual magnetic spectrometer system, consisting of Grand Raiden (GR) and Large Acceptance Spectrometer (LAS). Both GR and LAS consisted of magnets, two multi-wire drift chambers (MWDCs), and two plastic scintillators. The laboratory angles of GR (25.5\(^\circ\)) and LAS (51.0\(^\circ\)) relative to the beam and their magnetic fields were chosen to maximize the cross section of the ($p, 2p$) reaction leading to the s-hole state when the recoil momentum of the residual nucleus is zero. The $\Delta E$ signals of the plastic scintillators were used for particle identification, and were also used as trigger signals. The solid angles of the spectrometers were 4.3 msr for GR and 20.0 msr for LAS, respectively. The momenta and scattering angles of protons were determined by a ray-tracing technique with MWDCs. The experimental details for the production of s-hole states in light nuclei via the ($p, 2p$) reaction lead- ing to the $Q$-value is given by $Q = E_x - Q_{\gamma}$, where $E_x$ is the excitation energy of the target nucleus, $Q_{\gamma}$ is the $\gamma$-ray energy of the target nucleus, and $Q_{\gamma}$ is the sum of the kinetic energies of the two emerging protons.

III. ANALYSIS

To identify the hole state, the excitation energy ($E_x$) is evaluated from the energies of two emerging protons measured by GR and LAS as follows:

\[ k_3 = k_0 - k_1 - k_2 \]

\[ E_x - Q = T_0 - (T_1 + T_2 + T_3), \]

where $k_i$ and $T_i$ are the momenta and kinetic energies of the incident proton ($i=0$), the emerging protons ($i=1,2$), and the recoiling residual nucleus ($i=3$), respectively. The $Q$-value is given by $Q = M - (m_p + M')$, where $M$, $M'$, and $m_p$ are the masses of the target $^{16}$O, residual nucleus $^{15}$N, and proton, respectively. Figure 1 shows: (a) the two-dimensional scatter plot of the kinetic energies of two protons measured by GR and LAS, (b) the excitation energy spectrum of $^{15}$N induced by the $^{16}$O($p, 2p$)$^{15}$N reaction after the accidental coincidence background is subtracted. The s-hole state is strongly excited in the higher excitation energy region ($E_x > 16$ MeV) and splits into a few sub-structures. This structure agrees qualitatively with the result of recent shell-model calculation. Two peaks at 0.0 and 6.32 MeV correspond to the $p$ 1/2$^-$ and 3/2$^-$ hole states, respectively. The small amounts of the $p$ 3/2$^-$ strength are also fragmented to the states of 9.93 MeV and 10.7 MeV.

In the analysis of the $\gamma$-rays from the hole states in $^{15}$N, we use the independent signal of each NaI scintillator to determine the $\gamma$-ray energy. Since we take the timing data of the proton beam and NaI scintillator hit, the accidental coincidence backgrounds are estimated by using the events in the neighboring beam bunches of the true coincident timing. Using the 6.32 MeV $\gamma$-ray from the 3/2$^-$ state, the time variation of each PMT gain is monitored and corrected for. The 6.32 MeV $\gamma$-ray data is obtained by gating on $E_x = 6.32$ MeV as shown in Fig. 2. In the following analysis, to estimate the $\gamma$-ray emission probabilities from the s-hole state in $^{15}$N, we generate $\gamma$-ray Monte Carlo (MC) simulations. We use GEANT 3 package for simulation of particle tracking. The energy resolutions of the $\gamma$-ray detectors are taken into account from the 6.32 MeV $\gamma$-ray data.

A. $\gamma$-rays with $E_\gamma < 10$ MeV

Figure 3 shows the decay scheme of the s-hole state in $^{15}$N. From the s-hole state in $^{15}$N, different particles are emitted. In Ref. [1], the yields of these emitted particles were measured with their energies. The fraction of the $\alpha$ emission was found to be very small and excited levels fed by proton, neutron, deuteron, and triton emissions were observed. Some of the residual nuclei remained in an excited state below the particle re-emission threshold. This indicates that secondary $\gamma$-rays are emitted.

The $\gamma$-ray data from the s-hole state are obtained by gating the two-proton events in the excitation-energy region at $E_x = 16-40$ MeV. In the higher excitation-energy region, the signal-to-noise ratio becomes worse, because the detection efficiencies decrease gradually due to the finite momentum acceptance of the spectrometers. Therefore, we do not use the data with $E_x > 40$ MeV. The s-hole state has sub-structures as mentioned above. To specify $\gamma$-ray emissions from each sub-structure, the data is divided into three regions, $E_x = 16-20$ MeV, $E_x = 20-30$ MeV, and $E_x = 30-40$ MeV, which are indicated as A, B, and C in Fig. 1(b), respectively. Figure 4 shows the $\gamma$-ray energy distributions obtained by gating the two-proton events in these three excitation-energy regions. High energy $\gamma$-rays which are within the detectable range.
FIG. 1: (a) The two-dimensional scatter plot of the kinetic energies of two protons ($E_p$) measured by GR and LAS in the $^{16}$O$(p,2p)^{15}$N reaction. (b) The excitation energy spectrum of $^{15}$N induced by the $^{16}$O$(p,2p)^{15}$N reaction. The region shown by an arrow is scaled by 1/10. In the analyses of the $\gamma$-ray from the s-hole state, we use the coincident data with two protons in the regions A ($E_x=16–20$ MeV), B ($E_x=20–30$ MeV), and C ($E_x=30–40$ MeV).

FIG. 2: The coincidence $\gamma$-ray spectrum with the NaI scintillators obtained by gating on the peak at $E_x=5.3–7.3$ MeV in the $^{16}$O$(p,2p)^{15}$N reaction. The open circles and histogram show the data and 6.32 MeV $\gamma$-ray MC, respectively.

FIG. 3: A decay scheme from the s-hole state in $^{15}$N. The bold solid lines show ground states. The narrow solid lines show all the possible excited states to emit de-excitation $\gamma$-rays below particle emission thresholds (the break lines), except for the 15.1 MeV state. The states in $^{13}$C are also fed by $p+n$ decay, and the states in $^{12}$C are fed by $d+n$ decay and $p+n+n$ decay. We do not show the $^{13}$N+$n+n$ decay since the two-neutron emission threshold is high (21.39 MeV).

In Super-Kamiokande are clearly observed in Fig. 4 (b) and (c).

In order to obtain accurate values for these $\gamma$-ray emission probabilities, we fit the data with the associated $\gamma$-ray MC simulations. We use the $\gamma$-ray data $E_\gamma=3.0–7.4$ MeV. Because many kinds of $\gamma$-ray energy are associated, we do not analyze data at $E_\gamma <3.0$ MeV. An upper limit on the $\gamma$-ray gate energy of $E_\gamma <7.4$ MeV is chosen because the highest excitation energy of the associated states below the particle emission thresholds is 7.34 MeV, as shown in Fig. 4.

From the excited states in Fig. 4 we choose candidate excited states that emit the $\gamma$-rays as listed in Table 1 for fitting. We omit the 3.95 MeV state in $^{14}$N because it mostly de-excites with $\gamma$-rays with $E_\gamma <3.0$ MeV. Since the energies of two $\gamma$-rays with $E_\gamma=7.01$ MeV and 7.03 MeV are very close, we treat these two $\gamma$-rays as mono-energetic. We generate sixteen $\gamma$-rays in the MC.
TABLE II: Candidate states to be generated by a particle emission from the s-hole state in $^{15}$N [20]. The emission probabilities for the $\gamma$-rays with $E_{\gamma} > 3$ MeV are shown. $N(k)/N_{\text{tot}}$ are obtained from the fitting. The numbers in the parentheses in the $N(k)/N_{\text{tot}}$ are the sums of $N(k)/N_{\text{tot}}$ at the 7.01 MeV state in $^{14}$C and the 7.03 MeV state in $^{14}$N and at the 6.09, 6.59, and 6.90 MeV states in $^{14}$C, respectively.

| Decay scheme | Energy level $\gamma$-ray energy (MeV) (ratio) $N(k)/N_{\text{tot}}$ |
|--------------|--------------------------------------------------------------------------------------------------|
| $^{14}$C+d   | 3.09 (1/2$^+$) 3.09 (100%) 3.0%                                                             |
| $^{14}$C+d   | 3.68 (3/2$^+$) 3.68 (99.3%) 4.2%                                                              |
| $^{14}$C+d   | 3.85 (5/2$^+$) 3.09 (120%) 4.6% 3.68 (36.3%) 3.85 (62.5%)                                      |
| $^{14}$N+n   | 4.44 (2$^-$) 4.44 (100%) 5.8%                                                                  |
| $^{14}$N+n   | 4.92 (0$^-$) 4.92 (97%) 5.2%                                                                   |
| $^{14}$N+n   | 5.11 (2$^-$) 5.11 (79.9%) 0.0%                                                                 |
| $^{14}$N+n   | 5.69 (1$^-$) 3.38 (63.9%) 4.5% 5.69 (36.1%)                                                    |
| $^{14}$N+n   | 5.83 (3$^-$) 5.11 (62.9%) 0.54%                                                                 |
| $^{14}$N+n   | 6.20 (1$^-$) 3.89 (76.9%) 0.0%                                                                 |
| $^{14}$N+n   | 6.45 (3$^-$) 5.11 (81.1%) 2.8% 6.44 (70.1%)                                                   |
| $^{14}$N+n   | 7.03 (2$^+$) 7.03 (98.6%) (6.7%)                                                               |
| $^{14}$C+p   | 6.09 (1$^+$) 6.09 (100%) (0.0%)                                                               |
| $^{14}$C+p   | 6.59 (0$^+$) 6.09 (98.9%) (0.0%)                                                               |
| $^{14}$C+p   | 6.73 (3$^+$) 6.09 (3.6%) 0.43%                                                                 |
| $^{14}$C+p   | 6.90 (0$^+$) 6.09 (100%) (0.0%)                                                               |
| $^{14}$C+p   | 7.01 (2$^+$) 6.09 (1.4%) 6.73 (34.3%) 7.01 (98.6%)                                             |
| $^{14}$C+p   | 7.34 (2$^-$) 6.09 (49.0%) 5.7% 6.73 (34.3%) 7.34 (16.7%)                                      |

TABLE III: Summary of systematic uncertainties (%) of $\sum_{k} N(k)$ with $E_{\gamma,\text{tot}}>6$ MeV and $E_{\gamma,\text{tot}}=3$–6 MeV.

| $E_{\gamma,\text{tot}}$ | Energy scale | Detector acceptance | State selection |
|------------------------|--------------|---------------------|-----------------|
| $>$ 6 MeV              | +1.0% -5.4%  | ±3.4%               | +0.90% -0.72%   |
| $=3$–6 MeV             | +3.5% -6.4%  | +5.8%               | +12.0% -9.3%    |

analysis, and $\gamma$-rays with $E_{\gamma,\text{tot}}=3$–6 MeV are in the partially detectable range. Therefore, we estimate the summed branching ratios of the $\gamma$-ray emission with $E_{\gamma,\text{tot}}>6$ MeV and $E_{\gamma,\text{tot}}=3$–6 MeV, and also estimate the systematic uncertainties of $\sum_{k} N(k)$ as summarized in Table III. We take into account the following systematic uncertainties: imperfect knowledge of $\gamma$-ray energy scale, detector acceptance, and selection of the fitting states. From the 0.2 MeV error of the energy scale, we estimated the uncertainty to be $\pm 1.6\%$ and $\pm 8.9\%$ for $E_{\gamma,\text{tot}}>6$ MeV and $E_{\gamma,\text{tot}}=3$–6 MeV, respectively. The uncertainty of the detector acceptance is estimated to be 3.4% using the 6.32 MeV $\gamma$-ray from the 3/2$^-$ p-hole state, because its decay branching ratio is 100%. To check the effect of the selection of the fitting states, we apply the same fitting method omitting any one of the fourteen states. We take the largest difference from the original result as the uncertainty. The summed emission branching ratios ($\sum_{k} (N(k)/N_{\text{tot}})$) with their systematic uncertainties are estimated to be $15.6\pm1.3^{+0.6\%}_{-1.0\%}$ and $27.9\pm1.5^{+3.4\%}_{-2.6\%}$ for $\gamma$-rays with $E_{\gamma,\text{tot}}>6$ MeV and $E_{\gamma,\text{tot}}=3$–6 MeV, respectively. This means that the large amount (about a half) of the s-hole state decays to the excited states of daughter nuclei after the particle emissions, which agrees with the results of particle-decay measurement [11] and supports the theoretical prediction by the SU(3) model [12].

We evaluate the total $\gamma$-ray emission probabilities from the s-hole state associated with proton decay in $^{16}$O. The emission probabilities ($P(k)$) are evaluated using the equation $P(k) = (S_p(s\text{-state})/8) \times (N(k)/N_{\text{tot}})$. The spectroscopic factor of the s-hole state in the excitation-energy region at $E_x=16$–40 MeV is estimated to be 1.6 using the distorted wave impulse approximation (DWIA) calculation [11] [27]. The uncertainty of the spectroscopic factor is estimated to be about 10% from the DWIA calculations using different optical potentials. The total $\gamma$-ray emission probabilities with $E_{\gamma,\text{tot}}>6$ MeV and $E_{\gamma,\text{tot}}=3$–6 MeV are estimated to be 3.1% and 5.6%, respectively. Because some extra s-hole strengths still exist at $E_x>40$ MeV, the total emission probability for the whole s-hole state become slightly larger. In addition to the simple direct knockout (p, 2p) reaction, the multi-step processes or correlated processes like (p, 3p) and (p, 2pn) reactions contribute the excitation spectrum. $N_{\text{tot}}$ in-

 simulations for seventeen states in total. We then estimate the yield of the states by fitting the $\gamma$-ray data with these MC simulations. The result of the best fitted MC simulations are shown in Fig. 8 (a), (b), and (c) in comparison with the data. The fitted lines reproduce the data well.

From the fitting result, the branching ratio to the state $k$ ($N(k)/N_{\text{tot}}$) is evaluated, where $N(k)$ is the number of events at the state $k$ and $N_{\text{tot}} ($=2.49×10^{4}$) is the number of two-proton events in the excitation-energy region at $E_x=16$–40 MeV in $^{15}$N. These branching ratios are summarized in Table I. Since Cherenkov light is generated from all decay $\gamma$-rays, the total de-excitation energy of $\gamma$ decay ($E_{\gamma,\text{tot}}$) determines the amount of Cherenkov light. These states de-excite only by emitting one or more $\gamma$-rays. Therefore, $N(k)/N_{\text{tot}}$ corresponds to the $\gamma$-ray emission branching ratio with the total energy of $E_{\gamma,\text{tot}}$ equivalent to the excitation energy of the state $k$. In Super-Kamiokande, $\gamma$-rays with $E_{\gamma,\text{tot}}>6$ MeV are well within the detectable energy range for the $p \to \bar{\nu} K^+$ decay.
cludes such non-quasi-free contributions. The difference between \((N(k)/N_{\text{tot}})_{s-\text{hole}}\) and \((N(k)/N_{\text{tot}})\) is estimated to be 15% for the extreme case that \(N(k)\) is zero for the non-quasi-free process. The proton decay is a slightly different process from the \((p, 2p)\) reaction, because the nuclear medium could affect the proton decay and not leave a simple hole state. The fraction of the correlated decay is estimated to be 10% by Ref. 28. In this paper, we evaluate the emission probabilities without this effect.

The \(\gamma\)-ray emission probabilities estimated for the 7.01 and 7.03 MeV states are less than half of Ejiri’s estimate 9. However, we found a few excited states to emit \(\gamma\)-rays with \(E_\gamma > 6\) MeV. Compared to the 4% \(\gamma\)-ray emission probability with \(E_\gamma > 6\) MeV estimated by Ejiri, our emission probabilities are estimated to be 3.1%. On the basis of the \((e, e')p\) result 14, the dominant 6.32 MeV \(\gamma\)-ray from the \(3/2^-\) \(p\)-hole state is expected to be emitted with 29\% \((P(6.32\text{ MeV }p_{3/2^-}) = S_p(6.32\text{ MeV }p_{3/2^-})/8 = 2.35/8).\) The emission probabilities of 3.1\% with \(E_{\gamma,\text{tot}} > 6\) MeV is found to be about 1/10 compared with that of the 6.32 MeV \(\gamma\)-ray. Moreover, we found that the emission probability with \(E_{\gamma,\text{tot}} = 3-6\) MeV is high, though no \(\gamma\)-rays are quoted in this energy region in Ref. 9. Especially, the 4.4 MeV \(\gamma\)-ray emission mainly from the \(^{12}\text{C}+t\) decay is strong, despite the high Q-value. This is consistent with the result of the particle-decay measurement 11. The reason why the triton decay probability is higher than that of \(\alpha\) decay is theoretically explained by the selection rule obtained from the spatial SU(3) symmetry 12.

B. 15.1 MeV \(\gamma\)-ray

A 15.1 MeV \(\gamma\)-ray is emitted mainly from the \(T=1, 1^+\) state in \(^{12}\text{C}\) which might be made from the \(s\)-hole state in \(^{15}\text{N}\). In the \(\gamma\)-ray data obtained by gating on the \(s\)-hole events in the excitation-energy region at \(E_x=16-40\) MeV, we search for a signal in the energy region at \(E_x=10-15.7\) MeV, where the peak is expected to be located based on the MC study. Figures 5(a) and (b) show the 15.1 MeV \(\gamma\)-ray MC simulation and data, respectively. We do not find any significant excess within the statistical uncertainty. The limit on the total emission probability including the \(s\)-hole strength of the 15.1 MeV \(\gamma\)-ray is estimated to be 0.38\% at 99% confidence level.

The branching ratio of the door-way \(s\)-hole state in \(^{15}\text{N}\) to the \(T=1, 1^+\) state in \(^{12}\text{C}\) has been recently calculated in the same manner as used in Ref. 13. The obtained value is about 0.04\% 20. Taking into account the 15.1 MeV emission branching ratio from \(T=1, 1^+\) state in \(^{12}\text{C}\) and the spectroscopic factor of the \(s\)-hole state in \(^{15}\text{N}\), the total emission probability is predicted to be \(\sim 0.007\%\). Although the statistical decay process from the \(s\)-hole state might contribute to produce the 15.1 MeV state in \(^{12}\text{C}\), much more statistics of the data is needed to find out the signal of 15.1 MeV \(\gamma\)-ray.

IV. CONCLUSION

We studied the de-excitation \(\gamma\)-rays from the excitation of the \(s\)-hole state in \(^{15}\text{N}\) via the \(^{16}\text{O}(p, 2p)^{15}\text{N}\) reaction. The emission branching ratio of \(\gamma\)-rays with more-than-6 MeV and 3–6 MeV from the \(s\)-hole state in the excitation-energy region of 16 to 40 MeV are estimated to be \(15.6\pm 1.3^{+0.6}_{-1.0}\%\) and \(27.9\pm 1.5^{+3.4}_{-2.9}\%,\) respectively. If we take into account the spectroscopic factor of the \(s\)-hole state, the total emission probabilities are found to be 3.1\% and 5.6\%, respectively. In water Cherenkov detector experiments, it is important to understand the decay process with \(\gamma\)-rays from the proton-hole state in \(^{15}\text{N}\). Especially for the proton decay search via \(p \rightarrow \nu K^+\) in Super-Kamiokande, this result is useful to reduce the systematic uncertainty of the detection efficiency. Moreover, we searched for the 15.1 MeV \(\gamma\)-ray from the \(s\)-hole state.
However, we do not find any signal. We estimate the upper limit on the emission probability to be 0.38% at 99% confidence level.

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