Branching ratios for deexcitation processes of daughter nuclei following invisible dinucleon decays in $^{16}$O

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Various theories beyond the standard model of particle physics predict the existence of baryon number violating processes resulting in nucleon decay. When occurring within an atomic nucleus, such a decay will be followed by secondary decays of the daughter nucleus unless its ground state is directly populated. In this paper, we estimate branching ratios for processes associated with dinucleon decays of the $^{16}$O nucleus. To this end, we use a simple shell model for the ground state of $^{16}$O. For dinucleon decays from the $1p_{1/2}$ and $1p_{3/2}$ configurations in $^{16}$O, we take into account the pairing correlation using the hole-hole Tamm-Dancoff approximation. For decays from the $1s_{1/2}$ configuration, which result in highly excited states in the daughter nucleus, we employ a statistical model with the Hauser-Feschbach theory. Our analysis indicates that the branching ratio for gamma-ray emission in the energy range between 5 and 9 MeV, which is relevant to low-threshold water Cherenkov experiments such as SNO+, is 2.42%, 51.7%, and 2.64% for the $nn$, $pp$, and $pn$ decays in $^{16}$O, respectively. In particular, emission of 6.09 MeV gamma-ray from $^{14}$C originated from the diproton decay of $^{16}$O has a branching ratio of as large as 48.6%.

I. INTRODUCTION

While a proton is stable in the standard model of particle physics, grand unified theories (GUTs) predict that it decays by violating baryon number conservation [1]. Similar decays are predicted for bound neutrons also. In fact, the Particle Data Group lists 73 possible decay modes, both for one-nucleon and two-nucleon decays [2]. A recent measurement by the Super-Kamiokande collaboration sets the lower limit on the proton lifetime at $1.6 \times 10^{34}$ and $7.7 \times 10^{33}$ years at 90% confidence level for the $p \rightarrow e^+\pi^0$ and $p \rightarrow \mu^+\pi^0$ modes, respectively [2]. See also Refs. [4, 5] for other nucleon decay searches.

Among the possible decay modes of nucleons, there are certain modes in which the final decay products are almost undetectable, such as $n \rightarrow \nu_e\nu_e\bar{\nu}_e$ and $nn \rightarrow \nu_e\bar{\nu}_e$. These are commonly referred to as invisible decays. When the nucleon decay takes place in a nucleus, the resulting daughter nucleus will generally be in an excited state. Such a state will de-excite to a lower energy state by emitting gamma-rays or nucleons. Even though the primary decay products are invisible, invisible nucleon decays can therefore still be detected by measuring the secondary decays of the daughter nucleus [8, 10]. This strategy has been pursued in the past [11, 14], but the lower limits on the lifetime for the invisible decay modes are typically a few orders of magnitudes lower than that for the visible modes involving charged particles, which have higher energies and are therefore easier to detect. For instance, the lower limits of lifetimes for the $n \rightarrow$ invisible and the $nn \rightarrow$ invisible modes have been reported to be $5.8 \times 10^{29}$ and $1.4 \times 10^{30}$ years at 90% confidence level, respectively [14].

To improve the current limits for invisible nucleon decay, low-background water Cherenkov detectors may be used. Notably, the SNO+ experiment is conducting a search for nucleon decay in $^{16}$O in its initial phase using 900 tons of ultra-pure water, with $5.4-9$ MeV being the favourable energy region where backgrounds are expected to be low [12, 17]. Thanks to recent upgrades to the detector electronics, a search using Super-Kamiokande may also be feasible [18].

It is crucial to estimate the branching ratios for the secondary decays of the daughter nucleus in order to extract a limit on the decay lifetime of nucleons, since experiments can only measure the gamma-ray yields/limits. While detailed studies on the branching ratios for the single nucleon decay modes in $^{16}$O exist [4, 11], no such study has been carried out for dinucleon decays in $^{16}$O to the best of our knowledge.

Thus, the aim of this paper is to calculate the branching ratios for the secondary decays of daughter nuclei generated by dinucleon decays in $^{16}$O. Such study is of considerable importance given that new searches for nucleon decay in water are currently ongoing [17]. To this end, we follow a similar approach as that in Ref. [10].

That is, for secondary decays associated with the dinucleon decay from the $1s_{1/2}$ orbit in $^{16}$O, we estimate the branching ratios using a statistical model code. On the other hand, for secondary decays for the dinucleon decay from the $(1p_{1/2})^2$ and the $(1p_{3/2})^2$ configurations, we use the experimentally known decay properties of low-lying states in the daughter nuclei.

II. BRANCHING RATIOS FOR SECONDARY DECAYS OF THE DAUGHTER NUCLEUS

$^{16}$O is a well known double-magic nucleus, and it is reasonable to assume that its ground state can be described with a simple shell model based on the mean field approximation. In this approximation, 8 neutrons and 8 protons in $^{16}$O occupy single-particle levels up to the $N = 8$ and
the $Z = 8$ shell gaps, respectively. That is, 4 nucleons (2 neutrons and 2 protons) are in the $1s_{1/2}$ state, 8 nucleons in the $1p_{3/2}$ state, and 4 nucleons in the $1p_{1/2}$ state, as schematically illustrated in Fig. 1. The observed single-particle energies $\epsilon$ [19] are summarized in Table I. Here, the energies for the $1p_{1/2}$ states are estimated from the one-nucleon separation energies of $^{16}\text{O}$, while the energies of the $1p_{3/2}$ states are from the excitation energies of the $3/2^-$ states in $^{15}\text{O}$ and $^{15}\text{N}$. The energies for the $1s_{1/2}$ states, on the other hand, are deduced from the $(p,2p)$ experiment [19, 23].

TABLE I: Empirical single-particle energies $\epsilon$ for neutrons and protons in $^{16}\text{O}$ [19]. See also Refs. [23, 24].

| state   | $\epsilon_0$ (MeV) | $\epsilon_0$ (MeV) |
|---------|--------------------|--------------------|
| $1p_{1/2}$ | -15.7             | -12.1              |
| $1p_{3/2}$ | -21.8             | -18.4              |
| $1s_{1/2}$ | -47.0             | -40.0 $\pm$ 8     |

A. Two-neutron decay in $^{16}\text{O}$

1. Decay from the $1p_{1/2}$ and $1p_{3/2}$ orbits

Let us first consider an invisible dineutron decay in $^{16}\text{O}$, such as $nn \rightarrow 2\nu$. This process takes place only when two neutrons are at a very short distance. We therefore consider a disappearance of a $0^+$ pair of two neutrons in the same single-particle orbit, for which the wave functions have a large spatial overlap [24]. Let us discuss first a disappearance of a neutron pair in the $1p_{1/2}$ and $1p_{3/2}$ states. If one assumes a naive shell model, the ground state of $^{14}\text{O}$ is populated when the neutron pair in $1p_{1/2}$ is removed, while the second $0^+$ state of $^{14}\text{O}$ is generated when a neutron pair in $1p_{3/2}$ disappears. In reality, one has to take into account the pairing correlation among neutrons, with which the ground state and the second $0^+$ state of $^{14}\text{O}$ are given by

$$\left|^{14}\text{O}(0^+_{1})\right\rangle \sim \alpha \left| (1p_{1/2})^{-2} \right\rangle + \beta \left| (1p_{3/2})^{-2} \right\rangle,$$
$$\left|^{14}\text{O}(0^+_{2})\right\rangle \sim -\beta \left| (1p_{1/2})^{-2} \right\rangle + \alpha \left| (1p_{3/2})^{-2} \right\rangle,$$

respectively. Here, $\left| (1p_{1/2})^{-2} \right\rangle$ and $\left| (1p_{3/2})^{-2} \right\rangle$ are 0-particle-2-hole states constructed by removing a neutron pair from the $1p_{1/2}$ and $1p_{3/2}$ states, respectively. The coefficients $\alpha$ and $\beta$ can be estimated using the hole-hole Tamm-Dancoff approximation [24], which is similar to a three-body model with a core+$2$ valence neutrons [25, 26]. Using a Woods-Saxon single-particle potential to reproduce the energies of the $1p_{1/2}$ and the $1p_{3/2}$ states, together with a simple contact interaction $\epsilon_{\text{pair}}(r,r') = -g\delta(r-r')$ between the hole states, where the strength $g$ is determined so that the empirical two-neutron separation energy of $^{16}\text{O}$, $S_{2n}(^{16}\text{O})$ = 28.89 MeV is reproduced, we obtain $\alpha = 0.971$ and $\beta = 0.239$. This indicates that a removal of a neutron pair from the $1p_{1/2}$ results in the ground state of $^{14}\text{O}$ with the probability of $\alpha^2 = 0.943$ and the second $0^+$ state at $5.92$ MeV with the probability of $\beta^2 = 0.057$. On the other hand, a removal of a neutron pair from the $1p_{3/2}$ leads to the ground state of $^{14}\text{O}$ with the probability of 0.057 and the second $0^+$ state with the probability of 0.943.

The branching ratios $B$ can then be obtained by multiplying the fractions of neutron pairs in each orbital. Since there are 4 neutron pairs in total in $^{16}\text{O}$, the fraction is 1/4 and 2/4 for $1p_{1/2}$ and $1p_{3/2}$, respectively. That is, the branching ratios for the direct population of the ground state and the second $0^+$ state in $^{14}\text{O}$ are given by

$$B(14O(0^+_{1})) = 0.25 \times 0.943 + 0.5 \times 0.057 = 0.264,$$
$$B(14O(0^+_{2})) = 0.25 \times 0.057 + 0.5 \times 0.943 = 0.486,$$

respectively. Notice that the one-proton separation energy of $^{14}\text{O}$ is $S_p(^{14}\text{O}) = 4.63$ MeV, and the second $0^+$ at $5.92$ MeV decays by emitting a proton to $^{13}\text{N}(\text{g.s.})$ with 100% probability [23, 24], as illustrated in Fig. 2.

2. Decay from the $1s_{1/2}$ orbit

Let us next consider a dineutron decay from the $1s_{1/2}$ orbit. The removal of the neutron pair from the $1s_{1/2}$ orbit results in a fragmentation of the strength in a wide energy region [9]. Following Ref. [10], we assume that the strength is distributed according to the Breit-Wigner function

$$f(E^*) = \frac{1}{4} \cdot \frac{2}{\pi \tau} \frac{\Gamma^2/4}{(E^* - E_0^*)^2 + \Gamma^2/4},$$

with the centroid energy of $E_0^* = -2\epsilon_n(1s_{1/2}) - S_{2n}(^{16}\text{O}) = 65.11$ MeV and the width of $\Gamma = 7$ MeV. Here, we have taken into account the fraction of neutron pairs for the $1s_{1/2}$ orbit, which is 1/4.
Such highly excited states of $^{14}$O decay by emitting a number of particles, such as neutrons, protons, deuterons, tritons, $^3$He, and $\alpha$-particles, as well as gamma-rays. We evaluate these decays using the statistical model provided by the TALYS software [28] with the default parameter set. This code uses the Hauser-Feshbach theory [29] with the Gilbert-Cameron level density [30] and the optical potentials of Koning and Debarroche [31].

![Diagram](image.png)

**FIG. 2**: A decay scheme for the second $0^+$ state in $^{14}$O originated from the dineutron decay from the $1p_{1/2}$ and $1p_{3/2}$ orbits in $^{16}$O.

The results of the TALYS calculation are summarized in Tables II and III for the branching ratios of the final decay products and those of the dominant discrete gamma-ray emissions, respectively. For the former, we have included the contributions from the decays from the $1p_{1/2}$ and the $1p_{3/2}$ orbits. The gamma-ray spectrum is shown in Fig. 3 as a function of the gamma-ray energy $E_\gamma$.

Since the dineutron decays from the $1p_{1/2}$ and the $1p_{3/2}$ configurations of $^{16}$O result in the direct population of the ground state of $^{14}$O and $^{13}$N without gamma-ray emission (see Fig. 2 and Table III), the gamma-ray branch originates entirely in the decay from the $1s_{1/2}$ configuration. Because of the high excitation energies, the gamma-ray spectrum is distributed in a wide range of energies, as shown in the top panel of Fig. 3. There are no significant peaks in the region not shown in the figure, with the integrated branching ratio being 1.17% for $E_\gamma > 10$ MeV. The gamma-ray spectrum in the experimentally feasible range (5 MeV $\leq E_\gamma \leq 9$ MeV) is shown in the bottom panel of Fig. 3. Since there is no important discrete gamma-rays in this region (see Table III), the branching ratio in this region is not large. The integrated branching ratio between 5 and 9 MeV is 2.42%.

**TABLE II**: Branching ratios $\mathcal{B}$ for the final decay products for the dineutron decays of $^{16}$O, in which g.s. stands for the ground state of each nucleus.

| Nucleus | $\mathcal{B}$ (%) | Nucleus | $\mathcal{B}$ (%) |
|---------|------------------|---------|------------------|
| $^{14}$O (g.s.) | 26.4 | $^{13}$N (g.s.) | 48.6 |
| $^{10}$B (g.s.) | 2.54 | $^9$B (g.s.) | 3.62 |
| $^9$Be (g.s.) | 3.30 | $^8$Be (g.s.) | 6.21 |
| $^7$Be (g.s.) | 2.03 | $^6$Li (g.s.) | 3.48 |

**TABLE III**: Branching ratios $\mathcal{B}$ for the dominant discrete gamma-ray emissions for the dineutron decays of $^{16}$O. The number in the parenthesis denotes the energy of each state.

| Nucleus | Transition | $E_\gamma$ (MeV) | $\mathcal{B}$ (%) |
|---------|------------|------------------|------------------|
| $^{10}$B | $1_1^+ (0.72) \rightarrow 3_1^+ (0.0)$ | 0.72 | 1.67 |
| $^9$B | $1/2_1^+ (1.50) \rightarrow 3/2_1^+ (0.0)$ | 1.50 | 1.50 |
| $^9$B | $5/2_1^+ (2.35) \rightarrow 1/2_1^+ (1.50)$ | 0.845 | 0.768 |
| $^8$Be | $5/2_1^+ (2.43) \rightarrow 3/2_1^+ (0.0)$ | 2.43 | 0.778 |
| $^8$Be | $1/2_1^+ (3.03) \rightarrow 0_1^+ (0.0)$ | 3.03 | 2.96 |
| $^7$Be | $1/2_1^+ (0.429) \rightarrow 3/2_1^+ (0.0)$ | 0.429 | 0.763 |

**FIG. 3**: (a) Spectrum of gamma-rays from secondary decays of $^{14}$O originated from the dineutron decay of $^{16}$O as a function of the gamma-ray energy $E_\gamma$. The width of the energy bins is 0.1 MeV. The accumulated branching ratio in the region not shown in the figure amounts to 1.17%. (b) Expanded view of the upper panel in the region of $5 \leq E_\gamma \leq 9$ MeV, which is particularly relevant to current experiments.
FIG. 4: A decay scheme for the second $0^+$ state in $^{14}\text{C}$ originated from the diproton decay from the $1p_{1/2}$ and $1p_{3/2}$ orbits in $^{16}\text{O}$.

B. Two-proton decay in $^{16}\text{O}$

Let us next discuss diproton decay from $^{16}\text{O}$, resulting in $^{14}\text{C}$. The discussion is almost the same as for the dineutron decay in the previous subsection. Assuming the same configurations as in $^{14}\text{O}$, the populations of the ground state and the second $0^+$ state at 6.59 MeV in $^{14}\text{C}$ are 26.4% and 48.6%, respectively. A big difference, however, is that the one neutron separation energy of $^{14}\text{C}$ is 8.176 MeV, and the second $0^+$ state decays to the first $1^-$ state at 6.09 MeV by emitting a 0.50 MeV gamma-ray with a 100% probability [27]. This state then decays to the ground state of $^{14}\text{C}$ by emitting a 6.09 MeV gamma-ray (see Fig. 4).

We estimate the branching ratios associated with the diproton decay from the $1s_{1/2}$ configuration using the TALYS code as in the dineutron decay discussed in the previous subsection. To this end, we use the mean excitation energy of $E_* = -2\epsilon_p(1s_{1/2}) - S_{2p}(^{16}\text{O}) = 57.67$ MeV, where $S_{2p}(^{16}\text{O}) = 22.33$ MeV is the two-proton separation energy of $^{16}\text{O}$. We use the width of $\Gamma = 7$ MeV as in the previous subsection. The results are shown in Fig. 5, Tables IV and V, where we have also included the contribution of diproton decays from the $1p_{1/2}$ and the $1p_{3/2}$ configurations. As one can see from the figures and tables, the gamma spectrum is dominated by the 0.50 MeV and the 6.09 MeV gamma-rays originating from the population of the second $0^+$ state associated with diproton decay from the $1p_{1/2}$ and $1p_{3/2}$ configurations. Because of this, the integrated branching ratio between $E_\gamma = 5$ and 9 MeV is now enhanced to 51.7%. Note that $E_\gamma = 6.09$ MeV is in the favourable region for SNO+ experiment, which provides an ideal opportunity to search for invisible diproton decay of $^{16}\text{O}$.

TABLE IV: Same as Table II but for the diproton decays of $^{16}\text{O}$.

| Nucleus   | B (%) |
|-----------|-------|
| $^{14}\text{C}$ (g.s.) | 75.0  |
| $^{11}\text{B}$ (g.s.)  | 3.55  |
| $^{10}\text{Be}$ (g.s.) | 2.80  |
| $^9\text{Be}$ (g.s.)  | 3.24  |
| $^7\text{Li}$ (g.s.)  | 3.19  |

C. Proton-neutron decay in $^{16}\text{O}$

1. The number of proton-neutron pairs

We next consider $pn$ decay in $^{16}\text{O}$, resulting in $^{14}\text{N}$. Again, because of the short ranged nature of dinucleon decay, we consider only the disappearance of a proton-neutron pair in the single single-particle orbit. In contrast to same-particle pairs (that is, $nn$ and $pp$), there are two possible proton-neutron combinations which have a large spatial overlap of wave functions: the isospin-singlet and the isospin-triplet configurations. These correspond to...
the spin-1 and spin-0 states, respectively.

Consider a single-particle state with the angular momentum \( j \). For a proton with \((j, m)\), where \( j_z = m \) is the \( z \)-component of the angular momentum, one can consider \( pn \) pairs with a neutron with either \((j, m)\) or \((j, -m)\). The combinations with \( j_z \neq \pm m \) do not have a large spatial overlap of wave functions, thus we do not consider them here. The total number of proton-neutron pair is therefore \( 2(2j + 1) \). The combination of \((j, m)_p\) \((j, m)_n\) leads to a spin triplet pair with the total angular momentum \( J = 1 \). On the other hand, the linear superpositions of the combinations of \((j, m)_p\) \((j, -m)_n\) and \((j, -m)_p\) \((j, m)_n\) lead to both the spin triplet pair with the total angular momentum \( J = 1 \) and the spin singlet pair with the total angular momentum \( J = 0 \). Therefore, out of \( 2(2j + 1) \) proton-neutron pairs, \( 3(2j + 1)/2 \) pairs form \( J = 1 \) states while \( 2(2j + 1)/2 \) pairs form \( J = 0 \) states.

For instance, for \( j = 1/2 \) there are 3 pairs with \( J = 1 \) and 1 pair with \( J = 0 \). For \( j = 3/2 \) on the other hand, there are 6 pairs with \( J = 1 \) and 2 pairs with \( J = 0 \). Therefore there are 16 proton-neutron pairs in total in \(^{16}\)O, of which there are 12 pairs with \( J = 1 \) and 4 pairs with \( J = 0 \). These factors have to be taken into account in calculating the branching ratios for the \( pn \)-decay.

| Nucleus | Transition | \( E^* \) (MeV) | \( B(\%) \) |
|---------|------------|----------------|----------|
| \(^{14}\)C | \( 0^+_2 \) (6.59) \( \rightarrow 1^+_1 \) (6.09) | 0.50 | 48.6 |
| \(^{14}\)C | \( 1^-_1 \) (6.09) \( \rightarrow 0^+_1 \) (0.0) | 6.09 | 48.6 |
| \(^{11}\)B | \( 1/2^+ \) (2.12) \( \rightarrow 3/2^- \) (0.0) | 2.12 | 0.769 |
| \(^{10}\)B | \( 1^-_1 \) (0.718) \( \rightarrow 3^-_1 \) (0.0) | 0.718 | 1.85 |
| \(^{10}\)Be | \( 2^+_2 \) (3.37) \( \rightarrow 0^-_2 \) (0.0) | 3.37 | 0.812 |
| \(^{9}\)Be | \( 5/2^- \) (2.43) \( \rightarrow 3/2^- \) (0.0) | 2.43 | 0.790 |
| \(^{7}\)Li | \( 1/2^- \) (0.478) \( \rightarrow 3/2^- \) (0.0) | 0.478 | 1.95 |

**TABLE V:** Same as Table III but for the diproton decays of \(^{16}\)O.

![FIG. 6: A decay scheme for the low-lying \( 0^+ \) and \( 1^+ \) states in \(^{14}\)N originated from the \( pn \) decay from the \( 1p_{1/2} \) and \( 1p_{3/2} \) orbits in \(^{16}\)O.](image)

respectively, with \( \alpha' = \sqrt{0.992} \) and \( \beta' = \sqrt{0.008} \). Therefore, the removal of a \( pn \) pair from the \( 1p_{1/2} \) and the \( 1p_{3/2} \) states lead to almost pure configurations with \(^{14}\)N(\(1^+_1\)) and \(^{14}\)N(\(1^+_2\)), respectively. Taking into account the number of \( pn \) pair in each orbit, the branching ratio for population of the first and the second \( 1^+ \) states in \(^{14}\)N therefore reads,

\[
\mathcal{B}^{[14]N(1^+_1)} = \frac{3}{16} \times 0.992 + \frac{6}{16} \times 0.008 = 0.189,
\]

\[
\mathcal{B}^{[14]N(1^+_2)} = \frac{6}{16} \times 0.992 + \frac{3}{16} \times 0.008 = 0.374,
\]

respectively.

The second \( 1^+ \) state at 3.95 MeV decays to the first \( 0^+ \) state at 2.31 MeV by emitting a 1.64 MeV gamma-ray, which decays to the ground state by emitting a 2.31 MeV gamma-ray \([27]\) as shown in Fig. 6.

**3. Decay from the \( 1p_{1/2} \) and \( 1p_{3/2} \) orbits (\( J = 0 \))**

Let us next discuss the disappearance of a \( J = 0 \) \( pn \)-pair from the \( 1p_{1/2} \) and \( 1p_{3/2} \) orbits in \(^{16}\)O. Assuming again the same configurations as in \(^{14}\)O, the population of the first state \( 0^+ \) state at 2.31 MeV and the second \( 0^+ \) state at 8.62 MeV in \(^{14}\)N is evaluated to be,

\[
\mathcal{B}^{[14]N(0^+_1)} = \frac{1}{16} \times 0.943 + \frac{2}{16} \times 0.057 = 0.666,
\]

\[
\mathcal{B}^{[14]N(0^+_2)} = \frac{1}{16} \times 0.057 + \frac{2}{16} \times 0.943 = 0.121,
\]

respectively.

As mentioned in the previous subsection, the first \( 0^+ \) state decay to the ground state of \(^{14}\)N by emitting a 2.31 MeV gamma-ray. On the other hand, the one-proton separation energy of \(^{14}\)N is 7.55 MeV, so the second \( 0^+ \) state decays to \(^{13}\)C (g.s.) by emitting a proton \([27]\) (see Fig. 6).
4. Decay from the $1s_{1/2}$ orbit

The branching ratios associated with the $pn$ decay from the $1s_{1/2}$ configuration are evaluated with the TALYS code using the mean excitation energy of $E_x = -\epsilon_p(1s_{1/2}) - \epsilon_n(1s_{1/2}) - S_{pn}(^{16}O) = 64.04$ MeV, where $S_{pn}(^{16}O)$ is the energy required to remove one proton and one neutron from $^{16}O$, and the width of $\Gamma = 7$ MeV. The results are shown in Fig. 7 and Tables VI and VII where we have added the contribution of $pn$ decays from the $1p_{1/2}$ and the $1p_{3/2}$ configurations. One can see that the gamma-ray spectrum is dominated by the $1.64$ MeV and $2.31$ MeV gamma-rays, which originate in decays from the $1p_{1/2}$ and $1p_{3/2}$ orbits. The gamma-ray contribution in the region $5 \leq E_\gamma \leq 9$ MeV is not large: the integrated branching ratio in this energy region is $1.12\%$, which is comparable to the gamma-ray contribution associated with the dineutron decay of $^{16}O$.

III. SUMMARY

We have evaluated the branching ratios associated with baryon number non-conserving dinucleon decays in $^{16}O$. In particular, we have investigated the gamma-spectra in the experimentally relevant energy region between $5$ and $9$ MeV. For the decays from the $1p_{1/2}$ and the $1p_{3/2}$ configurations in $^{16}O$, we took advantage of the known decay properties of the daughter nuclei, while for the decay from the $1s_{1/2}$ configuration we used the statistical model provided by the TALYS software. We also took into account the pairing correlation with the hole-hole Tamm-Dancoff approximation for the decays from the $1p_{1/2}$ and the $1p_{3/2}$ configurations. For the $nn$ and the $pn$ decays of $^{16}O$, we did not find appreciable branching ratios for gamma-rays in the region $5 \leq E_\gamma \leq 9$ MeV. In contrast, for the $pp$ decay, we found that the $6.09$ MeV gamma-ray has a large branching ratio of $48.6\%$. This is within the favourable energy region for the initial water phase of the SNO+ experiment, and provides a promising way to search for diproton decay in $^{16}O$.

The branching ratios evaluated in this paper, together with the branching ratios for the single-nucleon decays shown in Refs. [6, 10], will be necessary ingredients in evaluating the lower limit of the invisible nucleon decays. We expect that our results will be useful in both current and future experiments, such as SNO+.

TABLE VI: Same as Tables II and IV but for the $pn$ decays of $^{16}O$.

| Nucleus | Transition | $E_\gamma$ (MeV) | $B$ (%) |
|---------|------------|------------------|---------|
| $^{14}N$ (g.s.) | $1^+ (3.95) \rightarrow 0^+ (2.31)$ | 1.64 | 37.4 |
| $^{14}N$ | $0^+ (2.31) \rightarrow 1^+ (0.0)$ | 2.31 | 44.0 |
| $^{10}B$ | $1^+ (0.718) \rightarrow 3^+ (0.0)$ | 0.718 | 1.85 |
| $^9B$ | $1/2^- (1.50) \rightarrow 3/2^- (0.0)$ | 1.50 | 0.931 |
| $^9Be$ | $5/2^- (2.43) \rightarrow 3/2^- (0.0)$ | 2.43 | 0.839 |
| $^8Be$ | $2^+ (3.03) \rightarrow 0^+ (0.0)$ | 3.03 | 3.25 |

TABLE VII: Same as Tables III and V but for the $pn$ decays of $^{16}O$.

| Nucleus | Transition | $E_\gamma$ (MeV) | $B$ (%) |
|---------|------------|------------------|---------|
| $^{14}N$ (g.s.) | $0^+ (3.50$ | 0.52 | 14.9 |
| $^{14}N$ | $0^+ (3.03) \rightarrow 1^+ (0.0)$ | 3.03 | 3.25 |

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