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Neutron-Unbound Excited States of 23N

Abstract
Neutron unbound states in 23N were populated via proton knockout from an 83.4 MeV/nucleon 24O beam on a liquid deuterium target. The two-body decay energy displays two peaks at E1∼100keV and E2∼1MeV with respect to the neutron separation energy. The data are consistent with shell model calculations predicting resonances at excitation energies of ∼3.6MeV and ∼4.5MeV. The selectivity of the reaction implies that these states correspond to the first and second 3/2− states. The energy of the first state is about 1.3 MeV lower than the first excited 2+ in 24O. This decrease is largely due to coupling with the πp−13/2 hole along with a small reduction of the N=16 shell gap in 23N.

Keywords
Neutron states, proton knockout, neutron separation energy, nuclear structure, nuclear decays, unstable nuclei, radioactive beams

Disciplines
Atomic, Molecular and Optical Physics | Nuclear | Quantum Physics

Authors

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Neutron-unbound excited states of $^{23}\text{N}$

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Neutron unbound states in $^{23}\text{N}$ were populated via proton knockout from an 83.4 MeV/nucleon $^{24}\text{O}$ beam on a liquid deuterium target. The two-body decay energy displays two peaks at $E_1 \sim 100\text{keV}$ and $E_2 \sim 1\text{MeV}$ with respect to the neutron separation energy. The data are consistent with shell model calculations predicting resonances at excitation energies of $\sim 3.6\text{MeV}$ and $\sim 4.5\text{MeV}$. The selectivity of the reaction implies that these states correspond to the first and second $3/2^-$ states. The energy of the first state is about 1.3 MeV lower than the first excited $2^+$ state. This decrease is largely due to coupling with the $\pi_{3/2}^-$ hole along with a small reduction of the $N = 16$ shell gap in $^{23}\text{N}$.

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I. INTRODUCTION

Spectroscopy of nuclei with extreme $N/Z$ ratios can provide valuable insight into nuclear structure. Due to shifts in the single particle energies of exotic nuclei, classical shell closures can disappear while new shell gaps appear [1,2]. A well-known example of this is the “island of inversion,” located around $A \sim 32$, where a quenching of the $N = 20$ shell gap results in nuclei with ground states occupying the $pf$ shell instead of the $sd$ shell [3]. In the oxygen isotopes, there is substantial evidence for the breakdown of the $N = 20$ shell gap, and the appearance of $N = 16$ as a magic number [4–7]. This shift has been attributed to the tensor component of the $NN$ interaction [8,9] as well as three-body forces [10].

As one moves down the $N = 16$ isotones, the removal of protons from the $\pi 0d_{5/2}$ orbital enables the $\nu 0d_{3/2}$ orbital to move higher in excitation resulting in a large energy difference between the $\nu 1s_{1/2}$ and $0d_{3/2}$ orbits in oxygen [2]. At present, there are no reports of bound- or unbound-excited states in the lighter isotones $^{21}\text{N}$ and $^{22}\text{C}$. The measurement of these excited states can provide a better understanding of the changing shell structure in this region of the nuclear chart by extending our knowledge of the $N = 16$ gap into the proton $p$ shell. In this article, we present first experimental information on neutron-unbound excited states in $^{23}\text{N}$ populated via proton-knockout from $^{24}\text{O}$.

II. EXPERIMENTAL METHOD

The experiment was carried out at the National Superconducting Cyclotron Laboratory (NSCL) where a 140 MeV/nucleon $^{48}\text{Ca}$ beam impinged upon a $^9\text{Be}$ target with a thickness of 1363 mg/cm$^2$ to produce an $^{24}\text{O}$ beam at 83.4 MeV/nucleon. The A1900 fragment separator was used to select $^{24}\text{O}$ from the other fragmentation products, and the remaining beam contaminants were removed by time-of-flight in the off-line analysis. The $^{24}\text{O}$ beam proceeded to the experimental area where it impinged on the Ursinus College Liquid Hydrogen Target, filled with liquid deuterium (LD$_2$). Based on the design of Ryuto et al. [11], the LD$_2$ target is cylindrical with a diameter of 38 mm, a length of 30 mm, and is sealed with 125 $\mu$m-thick Kapton foils on each side.

A one-proton removal reaction from the $^{24}\text{O}$ beam created $^{23}\text{N}$ in an excited state above the neutron separation energy $S_n$, which promptly decayed to $^{22}\text{N}$. The resulting charged fragments were then swept 43.3$^\circ$ by a 4-Tm superconducting sweeper magnet [12] into a collection of position- and energy-sensitive charged-particle detectors.

Element identification was achieved via a $\Delta E$ vs. time-of-flight measurement, and isotope identification was obtained through correlations in the time-of-flight, dispersive position, and dispersive angle following the sweeper magnet. Additional information on this procedure can be found in Ref. [13]. The position and momentum of the charged fragments at the target were reconstructed using an inverse transformation matrix, obtained from the program COSY INFINITY [14,15].

The neutrons emitted in the decay of $^{23}\text{N}$ traveled undisturbed by the magnetic field towards the Modular Neutron Array (MoNA) [16] and the Large-area multi-Institutional
charged particles emitted in the decay of $^{23}\text{N}$. The best fit includes two-channel Breit-Wigners resulting from two states at 1.1 MeV (dashed-red line) and 2.4 MeV (dot-dashed-blue line). Background contributions are in shaded gray. The efficiency and resolution are shown in the inset as the blue histogram (left scale) and red-dashed line (right scale), respectively.

Scintillator Array (LISA). MoNA and LISA each consist of 144 bars of plastic scintillator with photomultiplier tubes on both ends and provide a measurement of neutron time-of-flight and position. Additional details on the experimental setup can be found in Refs. [17,18]. MoNA, LISA, and the sweeper provide a full kinematic measurement of the neutrons and charged particles emitted in the decay of $^{23}\text{N}$.

III. ANALYSIS

The two-body decay energy is defined as

$$ E_{\text{decay}} = M^* - M_{^{22}\text{N}} - m_n, $$

where $M^*$ is the invariant mass of the decaying system, $M_{^{22}\text{N}}$ the mass of $^{22}\text{N}$, and $m_n$ the neutron mass. The decay energy, $E_{\text{decay}}$, corresponds to the excitation energy in $^{22}\text{N}$ above the neutron emission threshold. The invariant mass of the two-body system is obtained from the experimentally measured four-momenta of $^{22}\text{N}$ and the first time-ordered interaction in MoNA-LISA. To remove interactions from background $\gamma$ rays, a time-of-flight gate on prompt neutrons in coincidence with $^{22}\text{N}$ fragments was applied. The observed two-body decay energy for $^{25}\text{N}$ is shown in Fig. 1, and displays two prominent peaks at $E_1 \sim 100$ keV and $E_2 \sim 1$ MeV. The efficiency and resolution of MoNA-LISA for the present setup are shown as a function of the decay energy in the inset.

A Monte Carlo simulation was used to model the decay of $^{23}\text{N}$. The simulation includes the beam characteristics, the reaction mechanism, and subsequent decay. The efficiency, resolution, and acceptance of the charged particle detectors, along with the response of MoNA-LISA, are fully incorporated into the simulation. Therefore the results of the simulation are directly comparable to the experimental spectra. The neutron interactions in MoNA-LISA were modeled with GEANT4 [19] and MENATE_R [20]. A modification was made to the $^{12}\text{C}(n,np)^{11}\text{B}$ inelastic cross section within MENATE_R to better agree with previous measurement [21] at $T_n = 90$ MeV. No qualitative change was observed in the shape of the simulated one-neutron decay energy spectrum when the inelastic cross sections for neutrons on carbon were increased or decreased by an order of magnitude in MENATE_R.

The input decay energy line shape was an energy dependent Breit-Wigner of the form

$$ \sigma_i(E) \sim \frac{\Gamma_i}{(E_0 - E)^2 + \frac{1}{4}(\Gamma_i^2)}, $$

where $E_0$ is the position of the peak and $\Gamma_i$ the energy-dependent width. Given that $^{22}\text{N}$ has two bound excited states [22], it is possible for the neutron decay to branch to multiple final states. To model this, the two-channel form of the Breit-Wigner was used with a common normalization:

$$ \sigma_{\text{tot}}(E) \sim \sigma_1(E; E_1) + \sigma_2(E; E_2), $$

where $E_i$ is the energy of each branch, and the width in the numerator $\Gamma_i$ becomes the partial-width $\Gamma_i$. The total widths $\Gamma_i^T$ replace the width in the denominator and are given by the expressions

$$ \Gamma_1^T = \Gamma_1(E) + \Gamma_2(E - E_{12}), $$

$$ \Gamma_2^T = \Gamma_1(E + E_{12}) + \Gamma_2(E), $$

where $E_{12} = E_1 - E_2$ is the energy difference between the channels, with $E_1$ denoting the higher-energy channel. For simplicity, the shift functions have been neglected.

While it is possible for higher-lying states to be present at $E_{\text{decay}} > 3$ MeV, they are not resolved in the data and treated as background. Nonresonant contributions were modeled with a Gaussian decay distribution with a central energy of $E_{\text{decay}}$ = 10 MeV and a width of $\sigma$ = 5 MeV. This choice of line-shape reproduces the relative velocity between the fragment and neutron well and has been used to describe nonresonant contributions in the decay of $^{24}\text{O}$, populated by knockout from $^{28}\text{F}$ [4].

The measured decay energy can be related to the excitation energy of $^{23}\text{N}$ by $E^* = E_{\text{decay}} + S_n$, where $S_n$ was calculated using the mass excesses from Gaudefroy et al. [23]. Their values of $\Delta M_{^{23}\text{N}} = 36.72(0.28)$ MeV and $\Delta M_{^{22}\text{N}} = 31.11(0.26)$ MeV result in a one neutron separation energy of $S_n = 2.46(0.38)$ MeV. This separation energy is about 700 keV higher than what is obtained using the masses in the 2012 AME [24]. The two-neutron separation energy is $S_{2n} = 4.67(0.30)$ MeV.

Using the mass excesses measured by Gaudefroy et al. [23], theoretical predictions for the excited states of $^{23}\text{N}$ are shown in Fig. 2 with various interactions based on Ref. [25] including the WBP, WBT, WBTM, and WBM Hamiltonians in addition to the continuum shell model (CSM) [26]. The WBTM and WBM interactions contain a 12.5% and 25% reduction of the neutron-neutron interaction strength in the $sd$ space. In the lighter nitrogen isotopes, a 12.5% reduction was necessary to reproduce the low-lying levels [22,27], while a 25% reduction was needed for the heavier carbon nuclei [22]. Proton excitations were limited to the $p$ shell, while neutron...
excitations were restricted to the sd shell. These calculations predict several excited states with spin-parity $1^{-}/2^{-}$, $3^{-}/2^{-}$, and $5^{-}/2^{-}$ in the vicinity of 3–5 MeV. Due to the selective nature of the proton removal reaction, it is not likely to populate a $5^{-}/2^{-}$ state in $^{23}N$ from $^{24}O$. A $5^{-}/2^{-}$ state in $^{23}N$ can be made by coupling of the $p_{1/2}$ proton hole to the $2^{+}$ state of the $^{24}O$ core, or by coupling of a $p_{3/2}$ proton hole to the $2^{+}$ or $1^{+}$ state in the $^{24}O$ core. The ground state of $^{24}O$ has very little to no overlap with these configurations in $^{23}N$.

The spectroscopic overlaps $C^2S$ between $^{23}N$ and $^{24}O$ were calculated using the WBP and WBT Hamiltonians in NUSHELLX [28] and are summarized in Table I. The largest overlap is with the ground state of $^{23}N$, which is bound and was not within the acceptance of the sweeper magnet in this experiment. The next strongest overlaps are for the $3^{-}/2^{-}$ states where the single-particle strength is fragmented. Given that the overlap for the first $1^{-}/2^{-}$ excited state is very small, the most likely candidate for the spin-parity of the observed state(s) is $3^{-}/2^{-}$.

It is important to note that $^{22}N$ has two bound excited states, one at 183 keV, and another at 1017 keV [22]. Although the spin-parities of these states are unknown, the tentative assignments of the ground, first, and second excited states are $0^{-}$, $1^{-}$, and $2^{-}$, respectively. Thus, the observed peaks in the two-body decay energy could correspond to transitions to the $2^{-}$ excited state of $^{22}N$ instead of the ground state or the first excited $1^{-}$ state. Although there are neutron-unbound states in $^{23}N$ that $^{23}N$ could decay to, the selection of $^{22}N$ in the sweeper eliminates any contributions from these branches in the two-body spectrum of $^{23}N$.

As it is not possible to discern between any number of degeneracies or level orderings that could produce the observed spectrum without measuring the emitted $\gamma$ rays, one has to rely on theoretical calculations. For this reason, the data are interpreted and fit within the context of the shell-model predictions.

Of the interactions considered here, none predict a state near threshold (see Fig. 2). The lowest $3^{-}/2^{-}$ state is predicted to be at approximately 1 MeV above $S_n$, with the second $3^{-}/2^{-}$ being about an MeV higher. The 100 keV peak then does not correspond to a decay to the ground state but rather a transition to the $2^{-}$ state in $^{22}N$, while the $E_2 \sim 1$ MeV peak is comprised of transitions to both the first-excited and ground state of $^{22}N$. While there are three possible final states, the splitting between the ground and first-excited state cannot be resolved due to the experimental resolution for decay energies above 1 MeV. For

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**TABLE I.** Spectroscopic overlaps between various $J^\pi$ in $^{23}N$ and the ground state of $^{24}O$, calculated using the WBP and WBT interactions [25].

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>WBP</th>
<th>WBT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{\text{calc}}$</td>
<td>$(^{23}N</td>
</tr>
<tr>
<td>$1^{-}/2^{-}$</td>
<td>0</td>
<td>1.9328</td>
</tr>
<tr>
<td>$1^{+}/2^{-}$</td>
<td>4.961</td>
<td>0.0025</td>
</tr>
<tr>
<td>$\sum C^2S$</td>
<td>1.9578</td>
<td>1.9529</td>
</tr>
<tr>
<td>$3^{-}/2^{-}$</td>
<td>3.610</td>
<td>1.4645</td>
</tr>
<tr>
<td>$3^{+}/2^{-}$</td>
<td>4.525</td>
<td>0.6480</td>
</tr>
<tr>
<td>$3^{+}/2^{-}$</td>
<td>5.215</td>
<td>0.1682</td>
</tr>
<tr>
<td>$3^{+}/2^{-}$</td>
<td>6.989</td>
<td>1.4324</td>
</tr>
<tr>
<td>$\sum C^2S$</td>
<td>3.7130</td>
<td>3.7209</td>
</tr>
</tbody>
</table>
this reason, the 0\(^{-}\) and 1\(^{-}\) states are treated as a single state at their average energy. Since the spacing between the two 3/2\(^{-}\) states is expected to be about an MeV, another state was assumed to be around \(\sim 2\) MeV. In addition, because the final states in \(^{23}\)N are only tentatively known, the \(t\) values are chosen to be consistent with the interpretation.

The assumption of a second excited state is qualitatively supported by the data, as the high-energy tail cannot be described without excessive widths. In order to fit the spectrum with a single two-channel Breit-Wigner, it is necessary for the 100 keV branch to be \(\ell = 0\) as the relative intensity of the peaks is driven by the partial widths. The cross section for \(\ell = 2\) drops rapidly as \(E_{\text{decay}}\) approaches zero and the 100 keV peak cannot be \(\ell = 2\) in the presence of another broad channel unless it has an even larger width.

The spectrum can also not be described with both channels being \(\ell = 0\), because the widths are coupled and the penetrability for \(\ell = 0\) is constant. Thus, if the 1 MeV channel is made excessively broad too so is the 100 keV branch and the fit fails to describe the data.

The single-particle decay width for the decay to the ground state is 200 keV for \(\ell = 2\). Examining the spectroscopic factors in Table I, we note that the 3/2\(^{-}\) single-particle strength is fragmented indicating that these states are mixed in their neutron configurations. Thus one would expect widths less than the single-particle width, and so the solution with a single state is neglected due to the large necessary width. The data are fit with two-channel Breit-Wigners resulting from two 3/2\(^{-}\) states separated by approximately 1 MeV.

Since the branching ratios are not constrained without the knowledge of the \(\gamma\)-ray decays in \(^{22}\)N, there are too many free parameters to uniquely describe the data. Therefore a set of narrow widths was chosen to reduce the parameter space. These widths are \(\Gamma_{0} = 150\) keV for the low-energy branches of the two states (\(\ell = 0\) and 400 keV (\(\ell = 0\)) and 300 keV (\(\ell = 2\)) for the high-energy branch of the first and second 3/2\(^{-}\) states, respectively.

The energies of the two 3/2\(^{-}\) are then minimized simultaneously after fixing the partial widths. In addition, the energy of each branch is required to be consistent during the minimization. The best-fit energies for the two 3/2\(^{-}\) states are \(E_{\text{decay}} = 1070 \pm 100\) keV, and \(E_{\text{decay}} = 2500^{+500}_{-700}\) keV. The errors in the fit parameters are approximate due to the fixed partial widths. They are purely statistical and are determined by the 1\(\sigma\) limit in the \(\chi^{2}\) minimization. Accounting for the separation energy places the first excited 3/2\(^{-}\) at \(E_{\gamma} = 3530 \pm 100\) (stat) \(\pm 400\) (sys) keV.

At present the uncertainties are too large to uniquely determine the contributions from the possible branchings two 3/2\(^{-}\) states would produce. In order to completely disentangle the spectrum, one would need to measure the emitted \(\gamma\) rays in a triple-coincidence measurement \((n + \gamma + \gamma\) in 23\(^{\text{N}}\). In 24\(^{\text{O}}\) the \(N = 16\) shell gap was calculated by taking the \((2J + 1)\) weighted average of the 1\(^{+}\) and 2\(^{+}\) excited states, as they are composed of \(1p-1h\) excitations above the 24\(^{\text{O}}\) ground state [4]. Similarly, the same can be done in 23\(^{\text{N}}\), but one needs to take into account four states as the 2\(^{+}\) and 1\(^{+}\) configuration of neutrons, \((\nu_{1}s_{1/2})\) \(\otimes\) \((\nu_{0}d_{3/2})\), can couple with the unpaired \(\pi_{0}p_{1/2}\) proton to give (5/2\(^{-}\), 3/2\(^{-}\)) and (3/2\(^{-}\), 1/2\(^{-}\)), respectively. The situation is further complicated by the fact that the \(1p-1h\) neutron configuration in 23\(^{\text{N}}\) will mix with the \(\pi_{0}p_{3/2}\) hole, lowering its energy.

In the WBP, WBT, WBTM, and WBM interactions, the lowest 3/2\(^{-}\) state in 23\(^{\text{N}}\) is indeed a mixture, with the occupation numbers giving a significant proton hole in the \(\pi_{p_{1/2}}\) and \(\pi_{p_{3/2}}\) orbitals, and a \((\nu_{1}s_{1/2})\) \(\otimes\) \((\nu_{0}d_{3/2})\) configuration of neutrons. One may write the wave function for the 3/2\(^{-}\) state as

\[
|^{23}\text{N}_{3/2^{-}}\rangle = \alpha|^{24}\text{O}_{g.s.}\rangle_{\pi p} + \beta|^{24}\text{O}_{2+}\rangle_{\nu p} + \gamma p_{1/2}^{-1} \otimes |^{24}\text{O}_{1+}\rangle + \text{c.c.},
\]

where \(\alpha\), \(\beta\), and \(\gamma\) are coefficients constrained by the normalization \(\alpha^{2} + \beta^{2} + \gamma^{2} = 1\). According to the WBP calculation, the pure \(\pi_{p_{3/2}}\) configuration comprises of roughly 37\% of the total wave function (\(\alpha \sim 1/\sqrt{3}\)), with the remaining amplitude shared equally between the 2\(^{+}\) and 1\(^{+}\) configurations.

Thus the energy of the lowest 3/2\(^{-}\) state depends on both the \(N = 16\) shell gap and the energy of the \(\pi_{0}p_{1/2}\) hole, which is dictated by the spin-orbit splitting. The splitting between the \(d_{3/2}s_{1/2}\) and \(p_{1/2}p_{3/2}\) orbitals can be altered within NUSHELLX to study this dependence.

Let \(\Delta\) denote the change in energy for either the \(d_{3/2}\) or \(p_{1/2}\) orbital for both protons and neutrons from their initial values in the WBP calculation, using the same model-space restrictions as before. Figure 3 shows the energy of the lowest 3/2\(^{-}\) state as

\[E(J = 3/2^{-}) = E_{i} + \Delta_{D^{3/2}}, \quad \Delta_{p_{1/2}^{-1}}\]

\[
\Delta = d_{3/2} - s_{1/2}, \quad \Delta = p_{1/2} - p_{3/2}
\]

FIG. 3. Energy dependence of the first-excited 3/2\(^{-}\) state on the shift, \(\Delta\), on the energy of the \(d_{3/2}\) orbital (solid-blue line) or \(p_{1/2}\) orbital (dashed-red line). The dotted black lines denote the energies of the pure \(1p-1h\) or \(\pi p_{3/2}^{-1}\) configurations in the initial calculation (\(\Delta = 0\)). The experimental energy determined in this work is denoted by the black square.

IV. DISCUSSION

The present measurement alone is not sufficient to fully determine the size of the \(N = 16\) shell gap in 23\(^{\text{N}}\). In 24\(^{\text{O}}\) the 0\(^{-}\) and 1\(^{-}\) states were assumed to be around \(\sim 2\) MeV. In addition, because the final states in 24\(^{\text{O}}\) are only tentatively known, the \(t\) values are chosen to be consistent with the interpretation.
a function of either the $N = 16$ shell gap (solid-blue line) or the spin-orbit splitting (dotted-red line). By increasing the energy of the $d_{3/2}$ or $p_{1/2}$ orbitals independently, the mixing between the configurations is reduced until they are separated at the asymptotes. In the case of the $d_{3/2}$ orbit, increasing the $N = 16$ shell gap causes the $1p-1h$ configuration to be prohibitively costly in energy thus the $3/2^-$ state is comprised entirely of the $\pi p_{3/2}^{-1}$ hole. Likewise, increasing the spin-orbit splitting causes the promotion of a particle from the $\pi p_{3/2}^{-1}$ to the $\pi p_{1/2}$ to be too energetic, and the lower energy configuration is instead the $1p-1h$ configuration across the $N = 16$ shell gap.

Evidence for the size of the $N = 16$ shell gap in $^{24}$O can be deduced from the energy of the first excited $2^+$ state as shown in Figure 4 of Ref. [4]. In order to calculate the equivalent energy in $^{23}$N one has to take the $(2J + 1)$ weighted average of the first $3/2^-$ and $5/2^-$ states. All Hamiltonians considered in Fig. 2 predict these two states to be nearly degenerate, thus the excitation energy of the $3/2^-$ measured in the present experiment can be used to estimate the equivalent $2^+$ energy.

The most recent ENDF evaluation lists the excitation energy of the first $2^+$ in $^{24}$O as $4.79(11)$ MeV [29], corresponding to the weighted average of $4.82(11)$ [4] and $4.75(14)$ [5]. A more recent measurement of $4.70(15)$ MeV [30] agrees with this evaluation.

The present value of the excitation energy of about 3.5 MeV for the $3/2^-$ state in $^{23}$N is 1.3 MeV lower than the $2^+$ state in $^{24}$O. In the limit of no mixing from the $p_{3/2}^{-1}$ hole configuration, $\Delta[(p_{1/2})^2] - 1$, the energy of the lowest $3/2^-$ increases from $3.61$ MeV to $4.24$ MeV which is $500$ keV lower than the excitation of the $2^+$ in $^{24}$O. The $N = 16$ shell gap, or the $(2J + 1)$ average of the four lowest states in the $1p-1h$ multiplet, is around $4.53$ MeV when the contributions from the $p_{3/2}^{-1}$ configuration are removed. This value is $300$–$400$ keV lower than in $^{24}$O where this average was found to be $4.95(16)$ MeV [4], thus the shell gap in $^{23}$N is comparable to $^{24}$O. The shift in the effective $2^+$ energy is largely due to the coupling to the $p_{1/2}$ hole. In order to confirm this experimentally the excitation energy of the $5/2^-$ state in $^{23}$N should be measured.

V. CONCLUSIONS

Neutron unbound excited states in $^{23}$N were populated via proton knockout from an $^{24}$O beam on a deuterium target. The two-body decay energy of $^{23}$N displays two prominent peaks at $E_1 \sim 100$ keV and $E_2 \sim 1$ MeV. Because the daughter nuclide $^{22}$N has two bound excited states, it is not possible to distinguish between degeneracies or multiple level schemes that may produce the observed energy differences in the two-body spectrum of $^{23}$N. A triple coincidence experiment detecting the $^{22}$N fragments, neutrons and $\gamma$ rays is necessary to measure the branchings to the different final states.

The data are consistent with several shell model interactions which predict a $3/2^-$ state at $\sim 1$ MeV and $\sim 2$ MeV above $S_e$ in $^{21}$N. Similar to the first excited $2^+$ state in $^{24}$O, the first of these two $3/2^-$ states can be used to estimate the $N = 16$ shell gap. Its excitation energy of about 3.5 MeV is significantly lower than the $^{24}$O $2^+$ state at $4.8$ MeV, however this reduction is largely due to configuration mixing with the $\pi p_{3/2}^{-1}$ hole, thus indicating only a slight a reduction of the $N = 16$ gap in nitrogen.

Finally, in order to compare these data directly it is necessary to measure the first excited $5/2^-$ state in $^{23}$N. A future experiment designed to populate this state, for example inelastic excitation of $^{23}$N, would be valuable. In addition, the distribution of single-particle strength for the $3/2^-$ will be vital to determining the $\pi p_{3/2}^{-1}$ centroid experimentally and further understanding the mixing between the $1p1h$ and $\pi p_{3/2}^{-1}$ configurations.

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