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Neutron Unbound Excited States of ^{23}N

M.D. Jones,[1,2,*] T. Baumann,[1] J. Brett,[3] J. Bullaro,[4] P.A. DeYoung,[3] J.E. Finck,[5] N. Frank,[4] K. Hammerton,[1,6] J. Hinnefeld,[7] Z. Kohley,[1,6] A.N. Kuchera,[1] J. Pereira,[1] A. Rabeh,[4] J.K. Smith,[1,2,†] A. Spyrou,[1,2] S.L. Stephenson,[8] K. Stiefel,[1,6] M. Tuttle-Timm,[4] R.G.T. Zegers,[1,2,9] and M. Thoennessen[1,2]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[3]*Department of Physics, Hope College, Holland, MI 49422-9000, USA*
[4]*Department of Physics and Astronomy, Augustana College, Rock Island, IL 61201, USA*
[5]*Department of Physics, Central Michigan University, Mount Pleasant, MI 48859, USA*
[6]*Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA*
[7]*Deparment of Physics and Astronomy, Indiana University South Bend, South Bend, IN 46634-7111, USA*
[8]*Department of Physics, Gettysburg College, Gettysburg, PA 17325, USA*
[9]*Joint Institute for Nuclear Astrophysics – Center for the Evolution of the Elements, Michigan State University, East Lansing, Michigan 48824, USA*

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Neutron unbound states in ^{23}N were populated via proton knockout from an 83.4 MeV/nucleon ^{24}O beam on a liquid deuterium target. The two-body decay energy displays two peaks at $E_1 \sim$ 100 keV and $E_2 \sim$ 1 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 MeV and $\sim$ 4.5 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^+ in ^{24}O. This decrease is largely due to coupling with the $\pi p_{3/2}^{-1}$ hole along with a small reduction of the N = 16 shell gap in ^{23}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 $\nu 0d_{3/2}$ orbits in oxygen [2]. At present, there are no reports of bound- or unbound-excited states in the lighter isotones ^{23}N and ^{22}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}N populated via proton-knockout from ^{24}O.

* mdjones@lbl.gov; Present Address: LBNL, Berkeley, CA 94720, USA

† Present Address: Reed College, 3203 SE Woodstock Blvd, Portland, Oregon 97202, USA

II. EXPERIMENTAL METHOD

The experiment was carried out at the National Superconducting Cyclotron Laboratory (NSCL) where a 140 MeV/nucleon ^{48}Ca beam impinged upon a ^{9}Be target with a thickness of 1363 mg/cm^2 to produce an ^{24}O beam at 83.4 MeV/nucleon. The A1900 fragment separator was used to select ^{24}O from the other fragmentation products, and the remaining beam contaminants were removed by time-of-flight in the off-line analysis. The ^{24}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 μm-thick Kapton foils on each side.

A one-proton removal reaction from the ^{24}O beam created ^{23}N in an excited state above the neutron separation energy S_n, which promptly decayed to ^{22}N. The resulting charged fragments were then swept 43.3° 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 ΔE 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}N traveled undisturbed by the magnetic field towards the Modular Neutron Array (MoNA) [16] and the Large-area multi-Institutional 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 Ref. [17, 18]. MoNA, LISA, and the sweeper provide a full kinematic measurement of the neutrons and charged particles emitted in the decay of ^{23}N.

III. ANALYSIS

The two-body decay energy is defined as:

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

where M^* is the invariant mass of the decaying system, $M_{^{22}\mathrm{N}}$ the mass of ^{22}N and m_n the neutron mass. The decay energy, E_{decay}, corresponds to the excitation energy in ^{23}N above the neutron emission threshold. The invariant mass of the two-body system is obtained from the experimentally measured four-momenta of ^{22}N and the first time-ordered interaction in MoNA-LISA. To remove interactions from background γ-rays, a time-of-flight gate on prompt neutrons in coincidence with ^{22}N fragments was applied. The observed two-body decay energy for ^{23}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}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}C(n,np)^{11}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:

$$\sigma_l(E) \sim \frac{\Gamma_l}{(E_0 - E)^2 + \frac{1}{4}(\Gamma_l^2)}$$

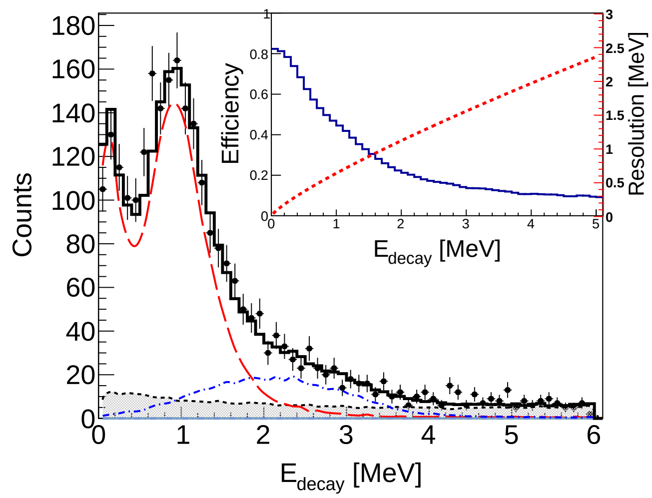

FIG. 1. (Color online) Two-body decay energy for ^{22}N + 1n. The best fit includes two-channel Breit Wigners resulting from two states at 1.1 MeV (dashed-red) and 2.4 MeV(dot-dashed-blue). Background contributions are in shaded-gray. The efficiency and resolution are shown in the inset as the blue histogram (left scale) and red-dashed line (right scale) respectively.

where E_0 is the position of the peak and Γ_l the energy-dependent width. Given that ^{22}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:

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

where E_i is the energy of each branch, and the width in the numerator Γ_l, becomes the partial-width Γ_i. The total widths Γ_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 $E_{decay} > 3$ MeV, they are not resolved in the data and treated as background. Non-resonant contributions were modeled with a Gaussian decay distribution with a central energy of $E_{decay} = 10$ 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 non-resonant contributions in the decay of ^{24}O, populated by knockout from ^{26}F [4].

The measured decay energy can be related to the excitation energy of ^{23}N by $E^* = E_{decay} + S_n$, where S_n was calculated using the mass excesses from Gaudefroy *et*

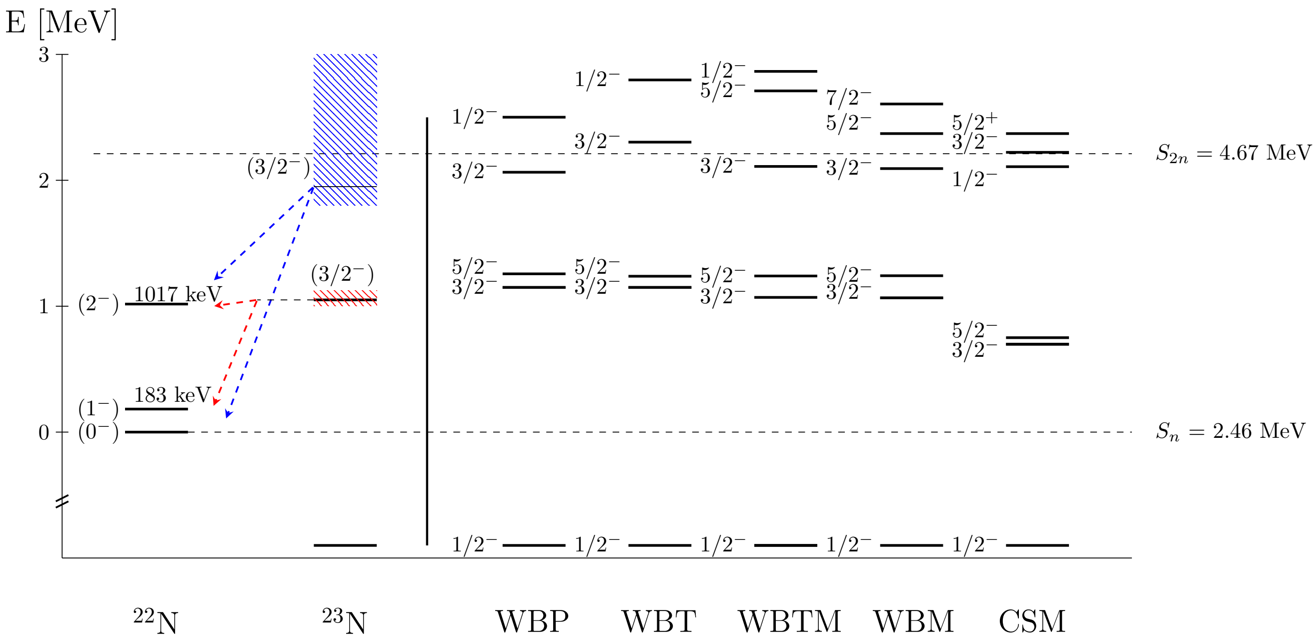

FIG. 2. A possible level ordering in ^{23}N consistent with the observed spectrum. The arrows indicate transitions from the first and second excited $3/2^-$ state in ^{23}N to various states in ^{22}N. The hatched areas indicate the experimental uncertainty given the assumptions discussed in the text. The colors correspond to the fit in Fig.1. The branching from the $3/2^-$ states to the various excited states of ^{22}N cannot be resolved without γ detection. Shell model calculations for ^{23}N are shown for comparison on the right.

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

	WBP		WBT	
J^π	E_{calc} (MeV)	$\langle ^{23}N \vert ^{24}O \rangle$ C^2S	E_{calc} (MeV)	$\langle ^{23}N \vert ^{24}O \rangle$ C^2S
$1/2^-_1$	0	1.9328	0	1.9529
$1/2^-_2$	4.961	0.0025	5.257	0
$\sum C^2S$		1.9578		1.9529
$3/2^-_1$	3.610	1.4645	3.610	0.6893
$3/2^-_2$	4.525	0.6480	4.764	1.0483
$3/2^-_3$	5.215	0.1682	5.471	0.0944
$3/2^-_4$	6.989	1.4324	6.693	1.8889
$\sum C^2S$		3.7130		3.7209

al. [24]. Their values of $\Delta M_{23N} = 36.72(0.28)$ MeV and $\Delta M_{22N} = 31.11(0.26)$ 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 [25]. The two-neutron separation energy is $S_{2n} = 4.67(0.30)$ MeV.

Using the mass excesses measured by Gaudefroy *et al.* [24], theoretical predictions for the excited states of ^{23}N are shown in Fig. 2 with various interactions based on Ref. [23] including the WBP, WBT, WBTM, and WBM Hamiltonians in addition to the Continuum Shell Model [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 ^{22}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 γ-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 Figure 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 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 ~ 2 MeV. In addition, because the final states in ^{22}N are only tentatively known, the ℓ 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 1 MeV peak to have $\ell = 2$ and a width of $\Gamma \sim 1.5$ MeV. In this scenario, it is also 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_{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 so too 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 γ-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 $\Gamma_i = 150$ 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 $E_{decay} = 1070 \pm 100$ keV, and $E_{decay} = 2500^{+500}_{-700}$ keV. The errors in the fit parameters are approximate due to the fixed partial widths. They are purely statistical and are determined by the 1σ limit in the χ^2 minimization. Accounting for the separation energy places the first excited $3/2^-$ at $E_x = 3530 \pm 100$ (stat) ± 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 γ-rays in a triple-coincidence measurement (n + γ + ^{22}N).

IV. DISCUSSION

The present measurement alone is not sufficient to fully determine the size of the N=16 shell gap in ^{23}N. In ^{24}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}O ground state [4]. Similarly, the same can be done in ^{23}N, but one needs to take into account four states as the 2^+ and 1^+ configuration of neutrons, $(\nu 1s_{1/2})^1 \otimes (\nu 0d_{3/2})^1$, can couple with the unpaired $\pi 0p_{1/2}$ 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}N will mix with the $\pi 0p_{3/2}$ hole, lowering its energy.

In the WBP, WBT, WBTM, and WBM interactions, the lowest $3/2^-$ state in ^{23}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 $(\nu 1s_{1/2})^1 \otimes (\nu 0d_{3/2})^1$ configuration of neutrons. One may write the wavefunction for the $3/2^-$ state as:

$$|^{23}N\rangle_{3/2-} = \alpha * p^{-1}_{3/2} \otimes |^{24}O\rangle_{g.s.} + \beta * p^{-1}_{1/2} \otimes |^{24}O\rangle_{2+} + \gamma * p^{-1}_{1/2} \otimes |^{24}O\rangle_{1+}$$

where α, β, and γ are coefficients constrained by the normalization $\alpha^2 + \beta^2 + \gamma^2 = 1$. According to the WBP calculation, the pure $\pi p^{-1}_{3/2}$ configuration comprises of roughly

37% of the total wavefunction ($\alpha \sim 1/\sqrt{3}$), 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 $\pi 0p_{3/2}^{-1}$ 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 Δ 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 a function of either the N=16 shell gap (solid-blue) or the spin-orbit splitting (dotted-red). 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 $\pi p_{3/2}$ 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 Reference [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 Figure 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 ENSDF 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, ($\Delta(p_{1/2}) \sim 1$), 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 $p_{3/2}$ hole. In order to confirm this experimentally the excitation energy of the $5/2^-$ state in ^{23}N should be measured.

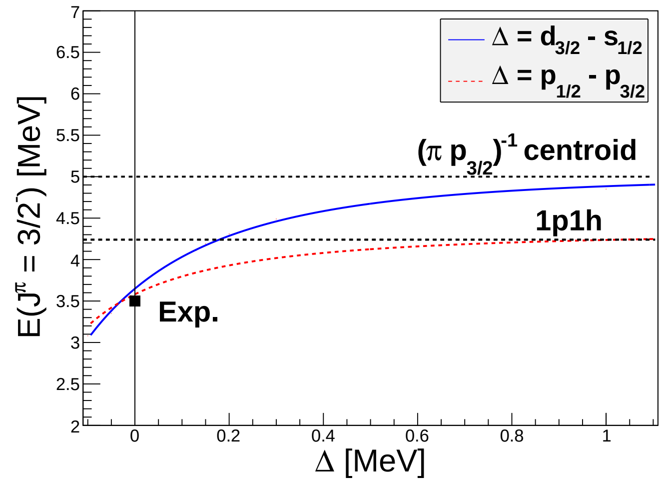

FIG. 3. (Color online) Energy dependence of the first-excited $3/2^-$ state on the shift, Δ, on the energy of the $d_{3/2}$ orbital (solid-blue) or $p_{1/2}$ orbit (dashed-red). The dotted black lines denote the energies of the pure 1p1h or $\pi p_{3/2}^{-1}$ configurations in the initial calculation ($\Delta = 0$). The experimental energy determined in this work is denoted by the black square.

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 γ-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_n in ^{23}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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[1] R. Kanungo, Physica Scripta **2013**, 014002 (2013).
[2] T. Otsuka, Physica Scripta **2013**, 014007 (2013).
[3] E. K. Warburton, J. A. Becker, and B. A. Brown, Phys. Rev. C **41**, 1147 (1990).
[4] C. Hoffman, T. Baumann, D. Bazin, J. Brown, G. Christian, D. Denby, P. DeYoung, J. Finck, N. Frank, J. Hinnefeld, S. Mosby, W. Peters, W. Rogers, A. Schiller, A. Spyrou, M. Scott, S. Tabor, M. Thoennessen, and P. Voss, Physics Letters B **672**, 17 (2009).
[5] K. Tshoo, Y. Satou, H. Bhang, S. Choi, T. Nakamura, Y. Kondo, S. Deguchi, Y. Kawada, N. Kobayashi, Y. Nakayama, K. N. Tanaka, N. Tanaka, N. Aoi, M. Ishihara, T. Motobayashi, H. Otsu, H. Sakurai, S. Takeuchi, Y. Togano, K. Yoneda, Z. H. Li, F. Delaunay, J. Gibelin, F. M. Marqués, N. A. Orr, T. Honda, M. Matsushita, T. Kobayashi, Y. Miyashita, T. Sumikama, K. Yoshinaga, S. Shimoura, D. Sohler, T. Zheng, and Z. X. Cao, Phys. Rev. Lett. **109**, 022501 (2012).
[6] R. Kanungo, C. Nociforo, A. Prochazka, T. Aumann, D. Boutin, D. Cortina-Gil, B. Davids, M. Diakaki, F. Farinon, H. Geissel, R. Gernhäuser, J. Gerl, R. Janik, B. Jonson, B. Kindler, R. Knöbel, R. Krücken, M. Lantz, H. Lenske, Y. Litvinov, B. Lommel, K. Mahata, P. Maierbeck, A. Musumarra, T. Nilsson, T. Otsuka, C. Perro, C. Scheidenberger, B. Sitar, P. Strmen, B. Sun, I. Szarka, I. Tanihata, Y. Utsuno, H. Weick, and M. Winkler, Phys. Rev. Lett. **102**, 152501 (2009).
[7] T. Baumann, A. Spyrou, and M. Thoennessen, Reports on Progress in Physics **75**, 036301 (2012).
[8] T. Otsuka, T. Suzuki, R. Fujimoto, H. Grawe, and Y. Akaishi, Phys. Rev. Lett. **95**, 232502 (2005).
[9] T. Otsuka, T. Suzuki, M. Honma, Y. Utsuno, N. Tsunoda, K. Tsukiyama, and M. Hjorth-Jensen, Phys. Rev. Lett. **104**, 012501 (2010).
[10] T. Otsuka, T. Suzuki, J. D. Holt, A. Schwenk, and Y. Akaishi, Phys. Rev. Lett. **105**, 032501 (2010).
[11] H. Ryuto, M. Kunibu, T. Minemura, T. Motobayashi, K. Sagara, S. Shimoura, M. Tamaki, Y. Yanagisawa, and Y. Yano, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **555**, 1 (2005).
[12] M. Bird *et al.*, IEEE Trans. Appl. Supercond. **15**, 1252 (2005).
[13] G. Christian *et al.*, Phys. Rev. C **85**, 034327 (2012).
[14] N. Frank, A. Schiller, D. Bazin, W. Peters, and M. Thoennessen, Nucl. Instrum. Methods Phys. Res., Sect. A **580**, 1478 (2007).
[15] K. Makino and M. Berz, Nucl. Instrum. Methods A **558**, 346 (2005).
[16] B. Luther *et al.*, Nucl. Instrum. Methods A **505**, 33 (2003).
[17] M. D. Jones, N. Frank, T. Baumann, J. Brett, J. Bullaro, P. A. DeYoung, J. E. Finck, K. Hammerton, J. Hinnefeld, Z. Kohley, A. N. Kuchera, J. Pereira, A. Rabeh, W. F. Rogers, J. K. Smith, A. Spyrou, S. L. Stephenson, K. Stiefel, M. Tuttle-Timm, R. G. T. Zegers, and M. Thoennessen, Phys. Rev. C **92**, 051306 (2015).
[18] M. D. Jones, Ph.D. thesis, Michigan State University. (2015).
[19] S. Agostinelli *et al.*, Nucl. Instrum. Mehtods A **506**, 240 (2003).
[20] B. Roeder, EURISOL Design Study, Report No. 10-25-2008-006-In-beamvalidations.pdf , pp. 31 (2008).
[21] D. A. Kellogg, Phys. Rev. **90**, 224 (1953).
[22] D. Sohler, M. Stanoiu, Z. Dombrádi, F. Azaiez, B. A. Brown, M. G. Saint-Laurent, O. Sorlin, Y.-E. Penionzhkevich, N. L. Achouri, J. C. Angélique, M. Belleguic, C. Borcea, C. Bourgeois, J. M. Daugas, F. D. Oliveira-Santos, Z. Dlouhy, C. Donzaud, J. Duprat, Z. Elekes, S. Grévy, D. Guillemaud-Mueller, F. Ibrahim, S. Leenhardt, M. Lewitowicz, M. J. Lopez-Jimenez, S. M. Lukyanov, W. Mittig, J. Mrázek, F. Negoita, Z. Podolyák, M. G. Porquet, F. Pougheon, P. Roussel-Chomaz, H. Savajols, G. Sletten, Y. Sobolev, C. Stodel, and J. Timár, Phys. Rev. C **77**, 044303 (2008).
[23] E. K. Warburton and B. A. Brown, Phys. Rev. C **46**, 923 (1992).
[24] L. Gaudefroy, W. Mittig, N. A. Orr, S. Varet, M. Chartier, P. Roussel-Chomaz, J. P. Ebran, B. Fernández-Domínguez, G. Frémont, P. Gangnant, A. Gillibert, S. Grévy, J. F. Libin, V. A. Maslov, S. Paschalis, B. Pietras, Y.-E. Penionzhkevich, C. Spitaels, and A. C. C. Villari, Phys. Rev. Lett. **109**, 202503 (2012).
[25] M. Wang, G. Audi, A. Wapstra, F. Kondev, M. MacCormick, X. Xu, and B. Pfeiffer, Chinese Physics C **36**, 1603 (2012).
[26] A. Volya and V. Zelevinsky, Phys. Rev. C **74**, 064314 (2006).
[27] M. J. Strongman, A. Spyrou, C. R. Hoffman, T. Baumann, D. Bazin, J. Brown, P. A. DeYoung, J. E. Finck, N. Frank, S. Mosby, W. F. Rogers, G. F. Peaslee, W. A. Peters, A. Schiller, S. L. Tabor, and M. Thoennessen, Phys. Rev. C **80**, 021302 (2009).
[28] B. Brown and W. Rae, Nuclear Data Sheets **120**, 115 (2014).
[29] B. Singh, Evaluated Nuclear Structure Data Files (ENSDF) (2015).
[30] W. F. Rogers, S. Garrett, A. Grovom, R. E. Anthony, A. Aulie, A. Barker, T. Baumann, J. J. Brett, J. Brown, G. Christian, P. A. DeYoung, J. E. Finck, N. Frank, A. Hamann, R. A. Haring-Kaye, J. Hinnefeld, A. R. Howe, N. T. Islam, M. D. Jones, A. N. Kuchera, J. Kwiatkowski, E. M. Lunderberg, B. Luther, D. A.

Meyer, S. Mosby, A. Palmisano, R. Parkhurst, A. Peters, J. Smith, J. Snyder, A. Spyrou, S. L. Stephenson, M. Strongman, B. Sutherland, N. E. Taylor, and M. Thoennessen, Phys. Rev. C **92**, 034316 (2015).