PHYSICAL REVIEW C **80**, 021302(R) (2009)

Disappearance of the $N = 14$ shell

M. J. Strongman,[1,2,*] A. Spyrou,[1,2] C. R. Hoffman,[3,†] T. Baumann,[2] D. Bazin,[2] J. Brown,[4] P. A. DeYoung,[5] J. E. Finck,[6] N. Frank,[1,2,‡] S. Mosby,[1,2] W. F. Rogers,[7] G. F. Peaslee,[5] W. A. Peters,[1,2,§] A. Schiller,[2,‖] S. L. Tabor,[3] and M. Thoennessen[1,2]

[1]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics, Florida State University, Tallahassee, Florida 32303, USA*
[4]*Department of Physics, Wabash College, Crawfordsville, Indiana 47933, USA*
[5]*Department of Physics, Hope College, Holland, Michigan 49423, USA*
[6]*Department of Physics, Central Michigan University, Mt. Pleasant, Michigan, 48859, USA*
[7]*Department of Physics, Westmont College, Santa Barbara, California 93108, USA*

(Received 10 July 2009; published 7 August 2009)

An excited state of ^{22}N unbound with respect to neutron emission was observed in a stripping reaction from a 85 MeV/nucleon ^{26}F beam. The observed decay energy of 650(50) keV places the level, which is interpreted to be the first 3^- state, at an excitation energy of 1.93(22) MeV. Together with the previously measured bound states of ^{22}N, reduction of the $N = 14$ shell gap compared to less neutron-rich nitrogen isotopes at the neutron dripline is observed. Based on the magnitude of the reduction of the shell gap for ^{22}N, a disappearance of the gap and even a level inversion of the $\nu 1s_{1/2}$ and the $\nu 0d_{5/2}$ levels in the neutron-unbound nucleus ^{21}C seems likely.

DOI: 10.1103/PhysRevC.80.021302 PACS number(s): 27.30.+t, 21.60.Cs, 25.60.−t, 29.30.Hs

The exploration of neutron-rich nuclei has revealed new magic numbers [1–3]. One such magic number is $N = 14$ which was first observed in ^{22}O as evidenced by the high excitation energy of the first excited 2^+ state [4–6] and low B(E2) value [4]. The large shell gap at $N = 14$ is thought to develop in the oxygen isotopes due to the attractive monopole matrix element $V^{\rm nn}_{d_{5/2}d_{5/2}}$ as neutrons fill the $\nu 0d_{5/2}$ orbit, increasing the binding relative to the $\nu 1s_{1/2}$ orbit [3]. Gamma-ray spectroscopy studies of bound excited states in ^{21}N [7] and ^{20}C [8] reveal a reduction of the $N = 14$ gap toward the neutron dripline compared to ^{22}O.

The evolution of a shell gap with neutron number N can be extracted from the single particle or single hole levels in the $N - 1$ or $N + 1$ nuclei. The first evidence for the disappearance of the $N = 8$ shell at the neutron dripline was the observation of the $\nu 0p_{1/2} - \nu 1s_{1/2}$ level inversion in the $N = 7$ nucleus ^{11}Be [9,10]. More recently the appearance of the $N = 16$ shell in neutron-rich oxygen isotopes was explored by measuring the single particle levels in ^{23}O [11] and ^{24}O [12], as well as the ground state energy of ^{25}O [13].

The gap between $\nu 1s_{1/2}$ and $\nu 0d_{5/2}$ is predicted to be largest for ^{22}O and will decrease with increasing distance from ^{22}O [8]. In the carbon isotopic chain, reducing the number of neutrons from ^{20}C ultimately leads to the inversion of the $\nu 1s_{1/2}$ and the $\nu 0d_{5/2}$ levels in ^{15}C [10,14]. A similar inversion is expected as neutrons are added to ^{20}C.

The size of the gap between the $\nu 1s_{1/2}$ and $\nu 0d_{5/2}$ orbitals has been determined for the $N = 15$ nucleus ^{23}O [15]. The spin and parity of the ground state of ^{23}O is $1/2^+$ ($\nu 1s_{1/2}$ particle state) and thus the measurement of the $5/2^+$ excited state ($\nu 0d_{5/2}$ hole state) at 2.79(13) MeV directly determines the size of the gap between the $\nu 1s_{1/2}$ and $\nu 0d_{5/2}$ orbitals. The excited state is unbound with respect to neutron emission and was measured via neutron spectroscopy. A recent γ-ray spectroscopy study of ^{22}N [7] observed two bound excited states which were interpreted as the first 1^- and 2^- states. The ground state of ^{22}N was assigned a spin and parity of 0^- by Ref. [7] guided by the shell model. In order to extract the magnitude of the $\nu 1s_{1/2}$–$\nu 0d_{5/2}$ gap, the location of the first 3^- state must be known. With the knowledge of the difference between the $\nu 1s_{1/2}$ and the $\nu 0d_{5/2}$ level in ^{23}O and ^{22}N, it is possible to predict the size of the gap or a possible inversion of the orbitals in ^{21}C using the linear extrapolation originally introduced by Talmi and Unna [10]. Because the 3^- state in ^{22}N is again above the neutron separation energy it is necessary to perform neutron coincidence measurements. We performed such an experiment by producing ^{22}N in a stripping reaction from a ^{26}F radioactive ion beam.

The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A ^{48}Ca^{+20} primary beam produced a 85 MeV/nucleon ^{26}F secondary beam via fragmentation in a 987 mg/cm^2 Be production target. Isotopic selection of the ^{26}F was achieved using the A1900 fragment separator [16], after which the secondary beam passed though two position sensitive parallel-plate avalanche chambers (PPACs) and then interacted with a 470 mg/cm^2 Be reaction target. ^{21}N and other recoil fragments were deflected by a large gap superconducting sweeper dipole magnet [17] with a bending angle of 43° and set to have a

*strongma@nscl.msu.edu
†Present address: Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA.
‡Present address: Department of Physics and Astronomy, Augustana College, Rock Island, IL 61201, USA.
§Present address: Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854, USA.
‖Present address: Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA.

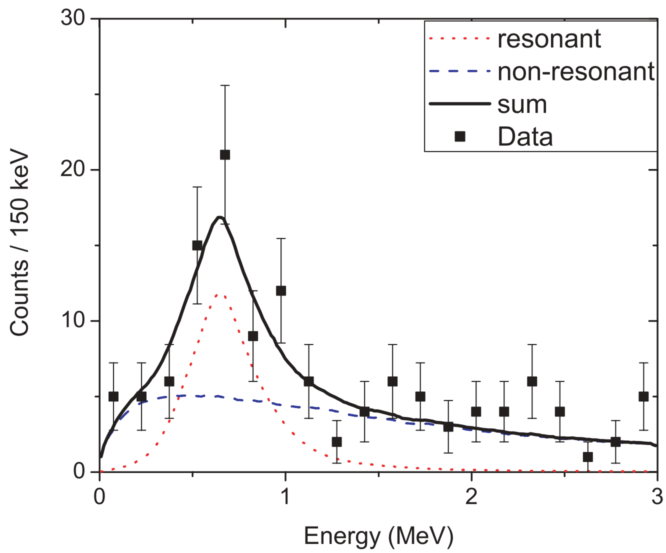

FIG. 1. (Color online) Neutron-decay energy spectrum of ^{22}N. The data with statistical error bars were measured by requiring a coincidence between an identified ^{21}N fragment and a neutron. The solid line is the sum of the resonant (dotted) and nonresonant (dashed) contributions of a Monte Carlo simulation that takes into account the resolutions and acceptances of the experimental apparatus. The resonance line-shape is a Breit-Wigner curve with $E_{\mathrm{decay}} = 0.65(5)$ MeV.

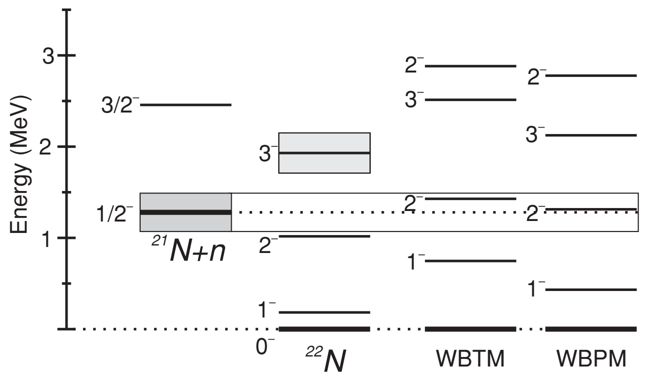

FIG. 2. Level scheme of ^{22}N. The present experimental data are shown together with the data of Ref. [7] and are compared to WBTM and WBPM shell model calculations. The neutron separation energy as well as the ground and first excited state of ^{21}N are also shown. The shaded area around the ^{21}N ground state represents the uncertainty due to the neutron separation energy. The shaded area around the measured 3^- state corresponds to the excitation energy uncertainty which is dominated by the uncertainty of the neutron separation energy.

magnetic rigidity of 3.7755 Tm. The Modular Neutron Array (MoNA) [18] detected the neutrons from the decay of ^{22}N leaving the target within an angular range of $\pm 7.0^\circ$ in the horizontal and $\pm 5.6^\circ$ in the vertical direction. Further details of the beam characteristics and the experimental setup can be found in Refs. [12,13].

Figure 1 shows the decay energy spectrum of neutrons in coincidence with ^{21}N. It exhibits a single resonance below 1 MeV superimposed on a background. In order to extract the resonance parameters, Monte Carlo simulations that included the detector resolutions and acceptances, were performed. The distribution was simulated with a single symmetric Breit-Wigner resonance in addition to a nonresonant contribution of a Maxwellian distribution with a thermal energy of 6.5 MeV. The determination of the resonance energy was insensitive to the peak energy of the Maxwellian distribution.

The decay energy and width of the resonance were determined by a χ^2 fit, where the amplitudes of the resonant and non-resonant contributions were free parameters. The best fit was achieved with a decay energy of $E_{\mathrm{decay}} = 0.65(5)$ MeV. The width of the resonance was dominated by the experimental resolution of the experimental setup and only an upper limit of 60 keV could be established from a 1-σ limit.

In order to extract the excitation energy of this resonance in ^{22}N it is necessary to add the binding energy to the decay energy. Adopting the accepted masses from Ref. [19], a neutron separation energy of 1.28(21) MeV can be calculated and results in an excitation energy of 1.93(22) MeV. It is interesting to note that although the statistics for the determination of the decay energy are rather limited, the uncertainty for the excitation energy is still dominated by the uncertainty of the mass measurement.

The spin and parity assignment of the observed resonance is guided by shell model calculations. This is a common approach to analyze states in nuclei far from stability where angular distribution measurements are difficult. The ground state of ^{22}N has been assigned a spin and parity of 0^- [7]. Sohler *et al.* [7] interpreted the two measured bound excited states at 183 keV and 1.017 MeV as the first 1^- and 2^- state, respectively. Since the 2^- level was found to be bound and thus below the neutron separation energy, the state we observe should be predicted to be above the 2^-. In a simplified single particle picture the 2p2n stripping reaction from ^{26}F can populate either the $\nu 1s_{1/2}$ particle, the $\nu 0d_{5/2}$ hole, or the $\nu 0d_{3/2}$ particle orbits. The first two couple to the 0^- or 1^- and 2^- or 3^- states discussed above, respectively. The latter orbit lies above the $N = 16$ gap and can couple to higher-lying 1^- and 2^- states which are most likely beyond the acceptance window of the current experimental setup. This is supported by evidence that the $N = 17$ nucleus ^{24}N is particle unbound [20]. The presently observed resonance corresponds most likely to the 3^- state. Figure 2 shows the level scheme of ^{22}N including the present data in addition to the recently determined bound states. The 0^- and 1^- states correspond to the coupling of the proton $\pi 0p_{1/2}$ state to the neutron $\nu 1s_{1/2}$ particle state while the 2^- and 3^- states arise due to the coupling of the proton $\pi 0p_{1/2}$ state to the neutron $\nu 0d_{5/2}$ hole state.

The 0^-, 1^-, and 2^- states are accounted for by the observation of the ground state and two excited bound states leaving the 3^- state as the most likely candidate for the presently observed resonance. The observed width of the resonance is also consistent with this interpretation. A $\nu 0d_{5/2}$ single particle state with a resonance energy of 650 keV yields $\Gamma_{sp} = 55$ keV [21]. The spectroscopic factor for the decay to the ground state of ^{21}N is 0.1059 (calculated via the shell model [22]), resulting in a width of $\Gamma = 6$ keV, which is well within the observed upper limit of 60 keV.

It should be mentioned that we cannot rule out the possibility that the observed resonance corresponds to a decay to a bound excited state of ^{21}N. The lowest measured excited state of ^{21}N (a $3/2^-$ state) is located at 1.177 MeV [7], which would place the resonance above 3 MeV in ^{22}N. This is unlikely because none of the most commonly used shell model interactions predict the first unbound excited state of ^{22}N at such a high excitation energy.

Sohler *et al.* [7] compared their results with shell model calculations using the WBT interaction [23] and a modified interaction WBTM, where the neutron-neutron interaction strength in the *sd* space (taken from the USD interaction [24]) was reduced by 12.5%. This reduction was justified by comparing the calculation to measured bound excited states of several neutron-rich nitrogen ($^{19-22}$N) and carbon ($^{17-20}$C) [8]. We reproduced these calculations using the code NuShell@MSU [22] and the results with the WBTM interaction are shown in Fig. 2. As can be seen, the calculated levels are consistently at higher excitation energies compared to the measured levels especially for the 1^- state. Calculations using the WBP Hamiltonian [23], which uses a different choice in the fitting of *psd* levels, showed an improvement in energy of the 1^- state. We applied the same 12.5% decrease of the neutron–neutron interaction strength to the WBP interaction (labeled as WBPM in Fig. 2) which resulted in an improved overall agreement with the data. The excitation energy of the 3^- calculated with the WBPM interaction is 2.12 MeV which is within the uncertainty of the presently measured resonance. It should be noted that the modified theoretical calculations of the 2^- state show that it is within the uncertainty of the neutron separation energy of ^{22}N.

As mentioned earlier, the size of the $N = 14$ gap, given by the difference between the $\nu 1s_{1/2}$ and $\nu 0d_{5/2}$ single-particle levels in ^{22}N, can now be calculated from the energy levels of the ground state and the first three excited states. The $2J + 1$ summing average [25] of the 0^- and 1^- states corresponds to the $\nu 1s_{1/2}$ level and the average of the 2^- and 3^- corresponds to the $\nu 0d_{5/2}$ level. The resulting shell gap for ^{22}N is 1.41(17) MeV, significantly smaller than the $N = 14$ shell gap of 2.79(13) MeV deduced for ^{23}O [15]. This reduction of 1.38(26) MeV in the $N = 15$ isotones is consistent with the reduction of 1 MeV reported between ^{22}O and ^{21}N for the $N = 14$ isotones [7]. The continuation of the reduction of the size of the shell gap and perhaps the emergence of a level inversion can be calculated using a linear interpolation first introduced by Talmi and Unna [10]. Figure 3 shows the

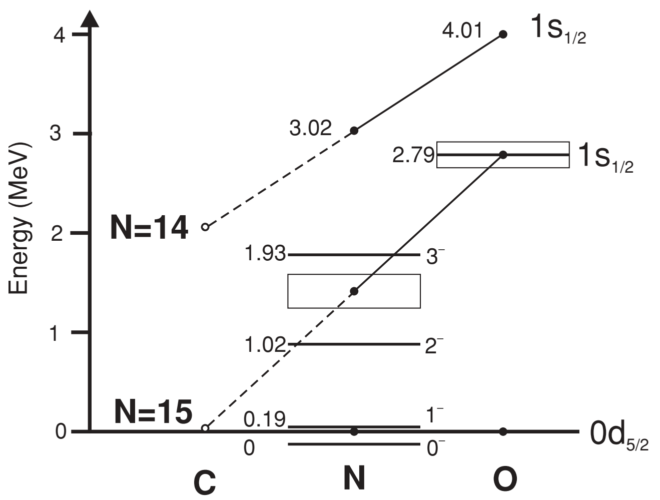

FIG. 3. The "competition" between the $\nu 0d_{5/2}$ and $\nu 1s_{1/2}$ levels for the $N = 15$ and $N = 14$ isotones of carbon, nitrogen, and oxygen following the prescription of Ref. [10]. Experimental data for the levels of ^{23}O and ^{22}N are taken from Refs. [7,8,15], and this work. The $\nu 1s_{1/2}$–$\nu 0d_{5/2}$ gap for ^{22}O and ^{21}N is taken from Refs. [7,8].

measured difference between the $\nu 1s_{1/2}$ and $\nu 0d_{5/2}$ levels for the $N = 14$ and $N = 15$ oxygen and nitrogen isotones and the extrapolation to ^{20}C and ^{21}C. While for ^{20}C, the $\nu 1s_{1/2}$ level is still 1.82 MeV above the $\nu 0d_{5/2}$ level, the levels are essentially degenerate (0.03 MeV) in ^{21}C. Within the experimental uncertainty the levels could be again inverted similar to the level inversion in ^{15}C [10].

In summary, we report the measurement of a neutron-unbound state of ^{22}N at 1.93(22) MeV assigned to the first 3^- state guided by the shell model. Combining this new result with the previously measured bound 1^- and 2^- states [7], we calculated the $N = 14$ shell gap in ^{22}N to be 1.41(17) MeV. This gap is small relative to the large gap of 4 MeV observed in the doubly-magic nucleus ^{22}O. This reduction can be attributed to the removal of a proton as well as the addition of a neutron. Extrapolating the present result to another proton removal leads to a potential inversion of the $\nu 1s_{1/2}$ and $\nu 0d_{5/2}$ orbits in ^{21}C. It would certainly be interesting to measure the ground state spin of ^{21}C in order to search for this inversion.

We would like to thank B. A. Brown for many enlightening discussions on the shell model. This work was supported by the National Science Foundation under Grant Nos. PHY-01-10253, PHY-03-54920, PHY-04-56463, PHY-05-02010, PHY-05-55366, PHY-05-55445, PHY-05-55488, and PHY-06-06007.

[1] R. V. F. Janssens, Nature **435**, 897 (2005).
[2] T. Otsuka *et al.*, Eur. Phys. J. A **15**, 151 (2002).
[3] O. Sorlin and M.-G. Porquet, Prog. Part. Nucl. Phys. **61**, 602 (2008).
[4] P. G. Thirolf *et al.*, Phys. Lett. **B485**, 16 (2000).
[5] M. Belleguic *et al.*, Nucl. Phys. **A682**, 136c (2001).
[6] M. Stanoiu *et al.*, Phys. Rev. C **69**, 034312 (2004).
[7] D. Sohler *et al.*, Phys. Rev. C **77**, 044303 (2008).
[8] M. Stanoiu *et al.*, Phys. Rev. C **78**, 034315 (2008).
[9] D. H. Wilkinson and D. E. Alburger, Phys. Rev. **113**, 563 (1959).
[10] I. Talmi and I. Unna, Phys. Rev. Lett. **4**, 469 (1960).
[11] Z. Elekes *et al.*, Phys. Rev. Lett. **98**, 102502 (2007).
[12] C. Hoffman *et al.*, Phys. Lett. **B672**, 17 (2009).
[13] C. Hoffman *et al.*, Phys. Rev. Lett. **100**, 152502 (2008).
[14] D. Alburger, A. Gallmann, and D. Wilkinson, Phys. Rev. **116**, 939 (1959).

[15] A. Schiller *et al.*, Phys. Rev. Lett. **99**, 112501 (2007).
[16] D. J. Morrissey *et al.*, Nucl. Instrum. Methods B **204**, 90 (2003).
[17] M. D. Bird *et al.*, IEEE Trans. Appl. Supercond. **15**, 1252 (2005).
[18] T. Baumann *et al.*, Nucl. Instrum. Methods A **543**, 517 (2005).
[19] R. B. Firestone, Nucl. Data Sheets **106**, 1 (2005).
[20] H. Sakurai *et al.*, Phys. Lett. **B448**, 180 (1999).
[21] B. A. Brown (private communication, 2009).
[22] B. A. Brown and W. D. M. Rae, NuShell@MSU (2007).
[23] E. K. Warburton and B. A. Brown, Phys. Rev. C **46**, 923 (1992).
[24] B. H. Wildenthal, Prog. Part. Nucl. Phys. **11**, 5 (1984).
[25] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957).