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Levels in ^{12}N via ^{14}N(p,t) using the JENSA Gas Jet Target

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As one of a series of physics cases to demonstrate the unique benefit of the new Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas jet target for enabling next-generation transfer reaction studies, the ^{14}N(p,t)^{12}N reaction was studied for the first time, using a pure jet of nitrogen, in an attempt to resolve conflicting information on the structure of ^{12}N. A potentially new level at 4.561 MeV excitation energy in ^{12}N was found.

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I. INTRODUCTION

A. JENSA

In this era of rare isotope beams, there has been a resurgence of studies involving transfer reactions, as such data are needed to ascertain the few-particle structure of levels of exotic nuclei and to inform a number of astrophysical processes. Exotic beams are usually of low intensity, however, and are often contaminated, sometimes severely so. Thus, in order to minimize undesirable spectral backgrounds, it is of utmost importance to utilize pure targets whenever possible, and this is especially a problem for the gaseous elements, such as hydrogen or helium, desired for many experimental studies.

The Jet Experiments in Nuclear Structure and Astrophysics (JENSA) system [1] is a recirculating, supersonic gas jet target for use in scattering, capture, and transfer reaction studies. The JENSA target will be central to a broad experimental program of reaction studies with low-energy reaccelerated beams at the Facility for Rare Isotope Beams (FRIB). JENSA was designed primarily for facilitating astrophysically-motivated reaction studies on hydrogen and helium, and is currently the densest helium jet target in the world [1]. However, during testing and commissioning, other gas species such as nitrogen were used. The JENSA target consists of a vacuum system surrounding the jet/interaction region, with space for charged-particle and γ-ray detectors (Figure 1), a series of high-throughput roots blowers and multistage roots blowers to move the gas from the interaction region, and a custom-built industrial compressor to raise the target gas from atmospheric pressure at the exhaust of the pumps to the high reservoir pressures necessary to create the jet. In this way, a target of gas that is highly localized ($\sim$4 mm), dense ($\sim 10^{18}$-10^{19} atoms/cm^2), and pure (fed directly from a research-grade gas cylinder), is produced.

The JENSA target provides a unique opportunity for scattering and reaction studies by surmounting several difficulties [1, 2]. For example, a pure gas jet target eliminates the background and scattering from either window material or from contaminants in a solid target compound (such as CH_2), thereby improving resolution and spectrum clarity (an excellent example may be found in Figure 6 of Ref. [2]). Because the target is a flowing gas, there is no concern over target degradation with increasing beam intensity. JENSA is optimized for exotic beam studies, having been designed to facilitate the use of large arrays of silicon strip detectors to achieve the large solid angle coverage needed for transfer reaction studies at low beam intensities.

B. ^{12}N

The evolution of nuclear shell structure as a function of neutron and proton excess is fundamental to a complete understanding of atomic nuclei. In particular, light nuclei provide an important testing ground for shell model theories, and such few-body systems are computationally accessible to a number of theoretical approaches, the development of which have implications for other areas of study. Determination of the nature of low-lying states in exotic light nuclei can challenge these theories within a relatively small model space, and transfer reactions on these light nuclei are an important tool for probing their structure. Transfer reaction studies with the JENSA gas jet target can improve on this time-tested technique.

The structure of unbound levels above the ground state in ^{12}N is a matter of some contention, particularly above

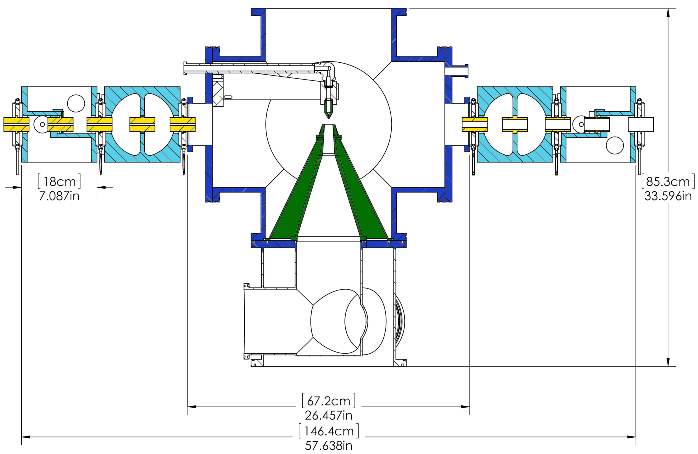

FIG. 1: (Color online) Scale drawing of the JENSA vacuum components, with a few dimensions for scale. Beam travels left to right. The light blue designates differential pumping stages, dark blue is the central chamber, green is the nozzle and receivers for the jet gas flow, and yellow are the restrictive apertures.

$\sim$3 MeV in excitation energy. Individual measurements over the years [3–17] have reported conflicting results, some of which also disagree with the most recent compilations [18, 19]. Several of the more recent measurements addressing the level structure of ^{12}N [10, 13] have relied heavily on mirror assignments and theoretical calculations, but many isobaric analogues in ^{12}B and ^{12}C remain unidentified in ^{12}N, and shell model calculations struggle as one moves from more bound (^{12}C, ^{12}B) to less bound (^{12}N) nuclei. Contributing to this lack of information, few transfer reactions have been used to study ^{12}N, and measurement of the (p,t) reaction on ^{14}N to populate ^{12}N levels (Q = -22.135 MeV) has not been reported [18, 19]. In this work, we have utilized the JENSA gas jet target for a measurement of the ^{14}N(p,t)^{12}N transfer reaction.

II. EXPERIMENT

A. JENSA experimental setup

For this measurement, the JENSA gas jet target system (see Fig. 1) was operated with a recirculating jet of ^{nat}N (99.632% ^{14}N) at 300 psig (pounds per square inch gauge pressure; this corresponds to an average density over the 4 mm jet width of $\sim$(5-6)$\times 10^{18}$ atoms/cm^2 [1]). A beam of 38 MeV protons was delivered from the Holifield Radioactive Ion Beam Facility 25 MV tandem accelerator through the gas-flow-restricting apertures of the JENSA system to the jet location. The resultant reaction products were detected in three ΔE-E SIlicon Detector ARray (SIDAR) [20] telescopes, calibrated with a ^{244}Cm alpha source of known activity and covering laboratory angles of $\sim 19-54°$, similar to previous studies [21]. Based on prior experience, the energy response of the detectors in this range is known to be linear. Tritons were isolated using standard ΔE-E techniques. Data were recorded for a total of just under 11 hours with proton beam intensities ranging from 1 to 4 nA.

B. Calibration

Figure 2 shows a spectrum of ΔE-E gated triton events for one laboratory angle, along with the expected locations of tritons from levels in ^{12}N up to 7.4 MeV from the latest ENSDF compilation [18]. A secondary calibration based on the few well-known singlet states (denoted by an asterisk in Table I) in ^{12}N was applied to these triton-gated data, and verified against a $\sim$30-keV-precision calibration based on the location of the ground state triton peak at two beam energies (30 and 38 MeV). Because the (p,t) reaction had not before been measured, it was not experimentally known which states would be populated via two-neutron pickup. As can be seen from Fig. 2, several particle-unbound levels in ^{12}N are reliably populated, in addition to the ground state. In all, nine peaks were conclusively observed. Background (around 11-12% overall, as determined from a gate of equal area above the tritons in the ΔE-E spectra) was caused by random coincidences due to the high count rates of scattered protons in the detectors; there is also a background of uncorrelated tritons (this can be seen to the right of the ground state peak in Fig. 2) which is likely due to the ^{11}C+p+t decay channel. There was no evidence for discrete features from different-mass contaminants, including ^{15}N (0.4% of ^{nat}N).

C. Excitation energies and widths

Excitation energies and widths were derived for each reliably-observed peak in the spectra by fitting the peaks with a Gaussian curve plus smooth background. The results are listed in Table I. The widths are taken to be the FWHM of each peak with the contribution from experimental resolution removed (as the experimental resolution varied slightly with angle, it was determined by the width of the ground state peak for each angle). Generally, the measured excitation energies and widths are in good agreement with the literature values (where available [18]), though population of the 4.140 and 7.40 MeV levels [18] is very weak and thus these assignments are only tentative. A broad continuum appears at higher E_x, up to the detector energy cutoff. Individual states are discussed below.

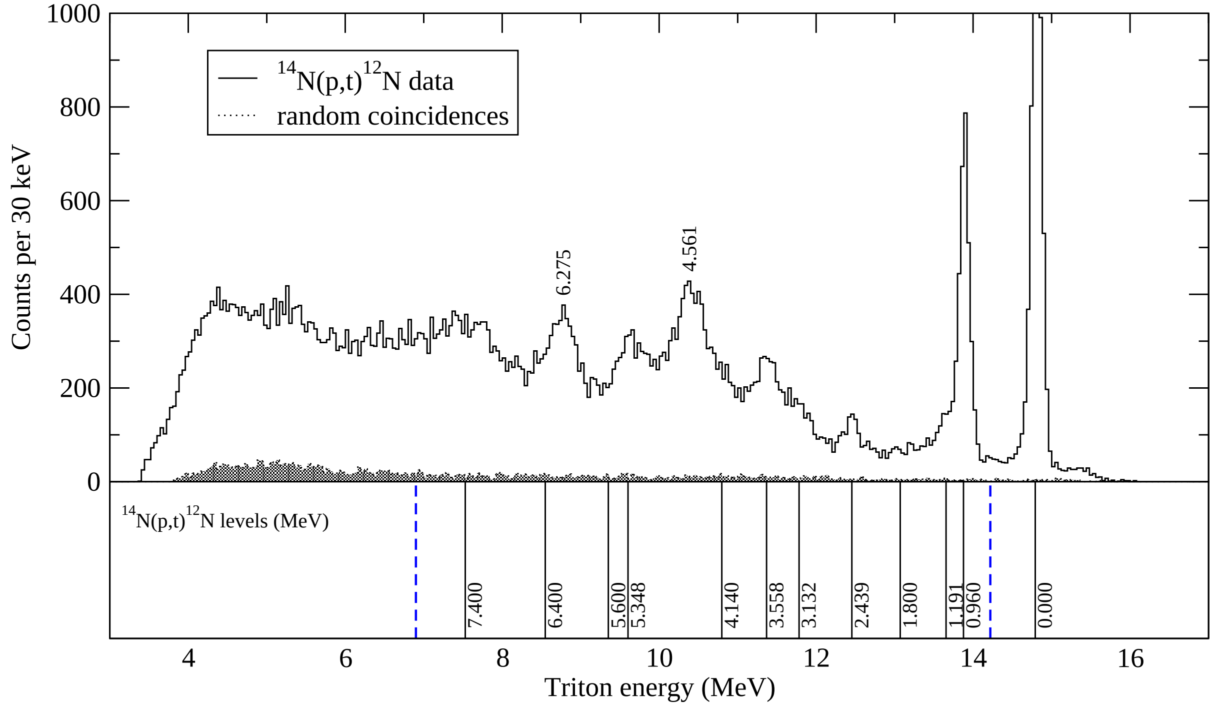

FIG. 2: (Color online) Triton energy spectrum at $\theta_{lab} = 32°$ (sum of all three detector telescopes) with adopted excitation energies in ^{12}N (from Ref. [18]) labeled in kinematically correct locations (not all known levels are populated). The particle thresholds in ^{12}N at $E_x = 0.601$ MeV (^{11}C+p) and $E_x = 8.007$ MeV (^{8}B+α) are shown in blue dashed lines. The two peaks labeled at the top of the figure are previously unidentified, as discussed in the text. The background due to random coincidences in the data acquisition system, as determined by a gate of equivalent area offset from the triton kinematic gate, is shown in grey shading.

D. Angular distributions and cross sections

Relative differential cross sections $\frac{d\sigma}{d\Omega}$ were extracted for each peak and scaled with respect to the strength of the ground state angular distribution at $\theta_{CM} \simeq 30°$. The extracted angular distributions were compared to finite-range DWBA calculations from DWUCK5 [22] for all possible transitions up to $L = 3$. Optical model parameters from the DWUCK5 test case for ^{40}Ca(t,p)^{42}Ca were used [22], and the binding energy of each single neutron was taken to be $S_{2n}/2$. L-transfers of 0 and 2 were considered by removing a $p_{3/2}$ neutron pair, whereas L-transfers of 1 removed neutrons from the $p_{3/2}$ and $d_{5/2}$ orbitals and L = 3 from the $p_{1/2}$ and $d_{5/2}$ orbitals. In the case of odd-L transfers, removal of a $p_{1/2}$ and $p_{3/2}$ pair was not considered, as the transfered neutrons must have opposite parity. While removal of a $p_{1/2}$ pair is possible, it was not considered in the current work as it would likely not differ significantly in shape to a $p_{3/2}$ pair, and is highly unlikely as the probability of finding a pair of $p_{1/2}$ neutrons in the ground state of ^{14}N is very low.

Figure 3 shows the calculated DWBA curves in comparison with the current data. The ^{12}N ground state very clearly follows an L = 2 curve, as do many of the other populated states (with some admixture also apparent; likely arising from complicated multi-step processes not considered in the current work and/or weak sd-shell admixtures in the ground state of ^{14}N [23]). However, this systematic population via L = 2 transfer is not unexpected, based on the 2s-1d configuration of the ^{14}N ground state [23]. For the strongly populated states, the L values derived in this work are generally consistent with previous spin and parity assignments (where known); individual cases are discussed below. Table I lists the L-transfer assignments and relative cross sections from this work.

While no absolute cross section was measured, some assumptions can be made to calculate a lower limit on the previously unmeasured ground state cross section. Integrating the normalized L = 2 curve over all angles gave a rough estimate of the total number of tritons produced. A maximum beam intensity of 4 nA was measured on a Faraday cup upstream of the JENSA target chamber; assuming a 100% transmission of the maximum beam intensity through the JENSA gas-restricting apertures (cf. Fig. 1) gives an upper limit for the amount of beam delivered on target. The beam spot on target was approximately a few millimeters in diameter, so the density of the 300psi nitrogen jet is taken to be the density over the central 2mm (Fig. 12 of Ref. [1]), which is most likely an overestimate of the number of target nuclei in the entire interaction region. Combining these estimates of target density and beam on target results in a mini-

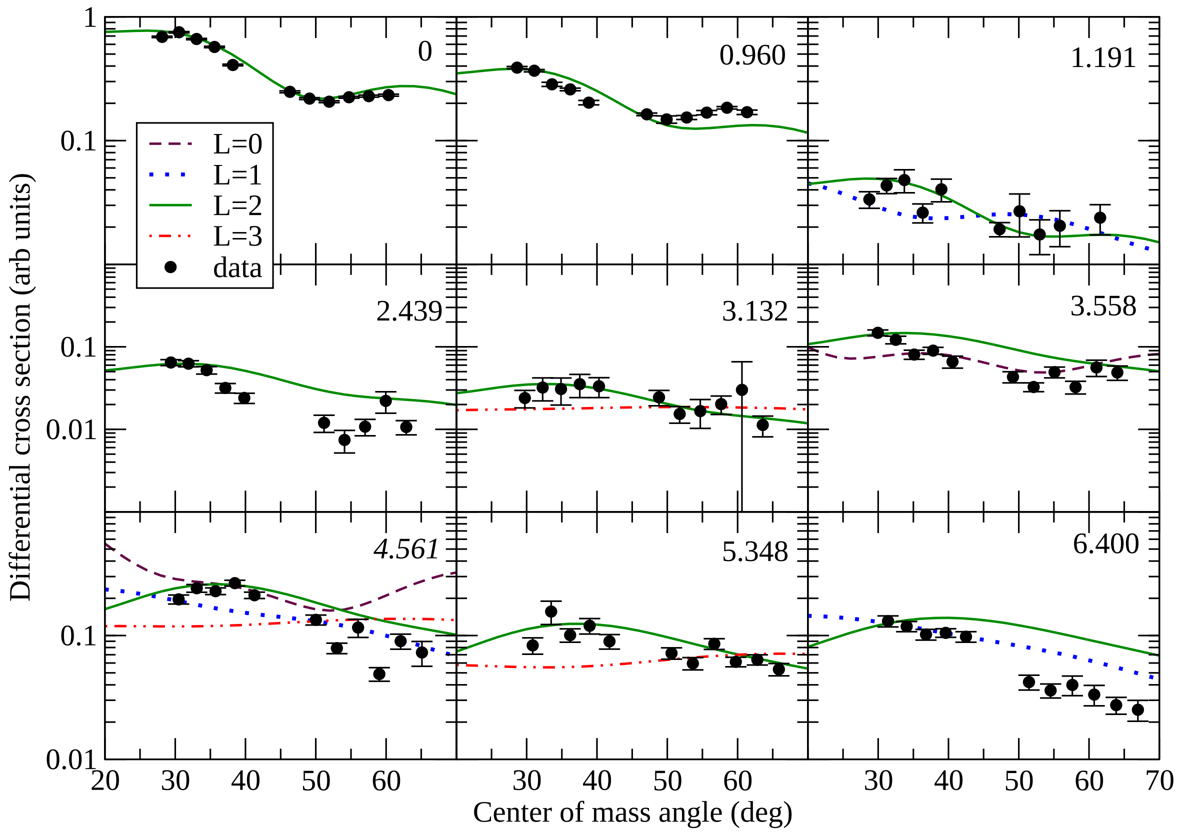

FIG. 3: (Color online) Measured angular distributions for all nine of the reliably populated states (labeled with the adopted literature value [18] in MeV, except for the new state at 4.561 MeV which is italicized), with DWBA calculations for comparison. As the J^π assignment for the 4.6 MeV state is completely unknown, all L-transfer values which were considered are plotted. L-transfers are shown as: L=0, purple dashed; L=1, blue dots; L=2, green solid; L=3, red dot-dash.

mum total cross section for ^{14}N(p,t) to the ground state of ^{12}N of 0.02 mbarns. This lower limit is in reasonable agreement with the calculated total cross section for the ground state from DWUCK5 of ∼0.07 mbarns, a good indication of the reliability of our experimental setup and a confirmation that the use of DWBA for analysis of the measured angular distributions is valid in this case.

III. DISCUSSION

There are several instances of disagreement with the literature (see Fig. 4). These are discussed in more detail below.

A. 0 to 3 MeV

The second excited state, at $E_x = 1.195$ MeV, is generally agreed to be 2^- spin and parity, which conflicts with the mostly L = 2 transfer measured in this work. However, the state is very weakly populated as a shoulder on the much stronger 0.956 MeV level, so it is possible that there is significant "contamination" of the weaker angular distribution from the adjacent strong positive parity state. Fitting various combinations of L transfer distributions to the data indicate that this peak potentially contains an L = 1 component of up to ∼20% strength. Additionally, the observance of the 1.195 MeV state could indicate that the likelihood of a multistep reaction process is high. Because of this uncertainty, we adopt the compilation J^π assignment. The 1.80 MeV level from the compilation, given its 1^- assignment, would not be populated strongly in the current work.

B. 3 to 4 MeV

Based on theoretical predictions and mirror arguments, both a 2^+ and 3^- level are expected around 3-4 MeV in ^{12}N; the known level at 3.132 MeV is assigned the 3^- spin and parity in Refs. [13] and [12], consistent with the tentative microscopic cluster model assignment [24]. However, the L = 2 transfer measured in the current work supports the assignment of 2^+ over 3^-. This assignment is in agreement with both Continuum-Coupled [27] and Ab Initio 3-Body Interaction [25] shell model calculations, both of which predict the second 2^+ level

TABLE I: ^{12}N level parameters and ^{14}N(p,t)^{12}N reaction parameters from this work, including statistical uncertainties. Calibration levels are labeled with a *. A comparison with the most recent compilation [18] is given. See also Figure 4 and descriptions in the text.

E_x (MeV) Ref. [18]	Width (MeV) Ref. [18]	E_x (MeV) current work	Width (MeV) current work	J$^\pi$ Ref. [18]	L-transfer current work	Adopted J$^\pi$ current work	$\frac{d\sigma}{d\Omega}$ rel. to g.s. at 30° current work
gs^*	sharp	gs	$< 0.179^a$	1^+	2	1^+	1
$0.960^* \pm 0.012$	< 0.020	0.956 ± 0.008	$< 0.179^a$	2^+	2	2^+	0.49 ± 0.01
$1.191^* \pm 0.008$	0.118 ± 0.014	1.195 ± 0.030	0.116 ± 0.074	2^-	1,2	2^-	0.06 ± 0.01
1.80 ± 0.030	0.750 ± 0.250			1^-			
$2.439^* \pm 0.009$	0.068 ± 0.021	2.438 ± 0.016	0.077 ± 0.092	0^+	2^b	0^+	0.09 ± 0.01
$3.132^* \pm 0.008$	0.220 ± 0.020	3.135 ± 0.019	0.217 ± 0.082	2^+, 3^-	2	2^+	0.03 ± 0.01
$3.558^* \pm 0.009$	0.220 ± 0.025	3.558 ± 0.007	0.245 ± 0.056	$(1)^+$	$(2,0)^b$	1^+	0.20 ± 0.02
4.140 ± 0.010^c	0.825 ± 0.025	(4.157 ± 0.102^d)		$2^- + 4^-$			
		4.561 ± 0.024^e	0.517 ± 0.072		$(2,0)^b$	$(1,2)^+$	0.26 ± 0.02
$5.348^* \pm 0.013$	0.180 ± 0.023	5.346 ± 0.009	0.340 ± 0.091	3^-	2	$(1,2,3)^+$	0.11 ± 0.02
(5.60 ± 0.11)	0.120 ± 0.050						
$6.40 \pm 0.030^{f,g}$	1.200 ± 0.030	6.275 ± 0.021	0.256 ± 0.088	(1^-)	$(1,2)^b$	$(1^-, 3^+)$	0.17 ± 0.02
7.40 ± 0.050^g	1.200 ± 0.030	(7.303 ± 0.108^d)	broad	(1^-)			

[a] Limit of experimental resolution. All widths other than that of the ground and first excited states have this contribution removed. See text.
[b] Likely admixture, based on qualitative assessment of DWBA curves. See text.
[c] ENSDF compilation [18] relies heavily on Refs. [6, 8] for this level; previous measurements [4, 5] place this level closer to $E_x = 4.25$ MeV.
[d] Only seen in a small, random subset of angles; the statistics are not sufficient to make a definitive assignment.
[e] Statistical uncertainty. Systematic uncertainty an additional ∼1 keV based on the energy calibration.
[f] Our assignment of the observed $E_x = 6.275$ MeV peak with this level is tentative. See text.
[g] According to compilation [18], this probably corresponds to unresolved states.

to appear around 3.1 MeV excitation energy in ^{12}N. Instead, both ^{11}C+p measurements [12, 13] associate this 2^+ state with the higher 3.558 MeV level, though the earlier experiment was unable to differentiate between 1^+ and 2^+ [12] and the latter placed the level about 100 keV lower than previously reported [13]. It is possible that the two levels (2^+, 3^-) are degenerate. The L = 2 transfer derived from this work is insufficient to differentiate between the possible 1^+ and 2^+ assignments in this excitation energy region [18]; however, as the 3.558 MeV level seems to demonstrate some L = 0 admixture (Fig. 3), it seems more likely that the 3.558 MeV level is 1^+, making the 3.132 MeV level 2^+.

C. 4 to 5 MeV, including a potentially new level

For the peak populated at $E_x = 4.561 \pm 0.024$ MeV (see Table I and Fig. 2), there is no known corresponding level in the compilations [18, 28, 29]. Ref. [4] reported a "broad level or group of levels" at 4.24 ± 0.05 MeV excitation energy; no additional information about the level is given. Ref. [5] reports a weakly-populated level at 4.25 ± 0.03 MeV, with a width of 0.3 MeV; however, the current work disagrees with these values by several sigma. In Ref. [10], angular distributions of a broad peak around $E_x \sim 4.3$ MeV, informed by analogy to $2^- + 4^-$ doublets in ^{12}B and ^{12}C, were used to disentangle two levels at 4.18 ± 0.05 MeV (2^-, 0.836 ± 0.025 MeV wide) and 4.41 ± 0.05 MeV (4^-, 0.744 ± 0.025 MeV wide). Since the peak in the current work falls at an excitation energy ∼150 keV above the higher of the two levels given in Ref. [10] and the measured widths do not agree, it is probable that the 4.561 MeV peak does not correspond to either. Similarly, Ref. [13] also observed a broad structure at $E_x \sim 4.3$ MeV, and an R-matrix analysis (based again on mirror arguments from ^{12}B) suggested the 2^- and 4^- levels to be at 3.924 and 4.300 MeV, respectively. The ∼ 0.6 MeV width derived for the 4^- state in Ref. [13] is in much better agreement with the value from the current work; however, the 4.300 MeV excitation energy is still lower than the 4.561 MeV from this work by almost 300 keV ($> 10\sigma$). In addition, the assignment by Refs. [10] and [13] of 2^- and 4^- to these levels is not consistent with our L = 2 angular distribution. Thus it seems unlikely that the populated level in this work is the same as the ∼ 4.3 MeV peak observed in previous studies [4, 5, 10, 13], as is demonstrated in Figure 5.

However, multiple analogues exist in ^{12}C and ^{12}B which remain unobserved in this region of ^{12}N [18]. The mainly L = 2 assignment for the unknown 4.561 MeV state is consistent with it being the analogue of the 5 MeV 1^+ level in ^{12}B. Shell model calculations predict a 1^+ ^{12}N level at $E_x = 4.392$ MeV [25] for which the ob-

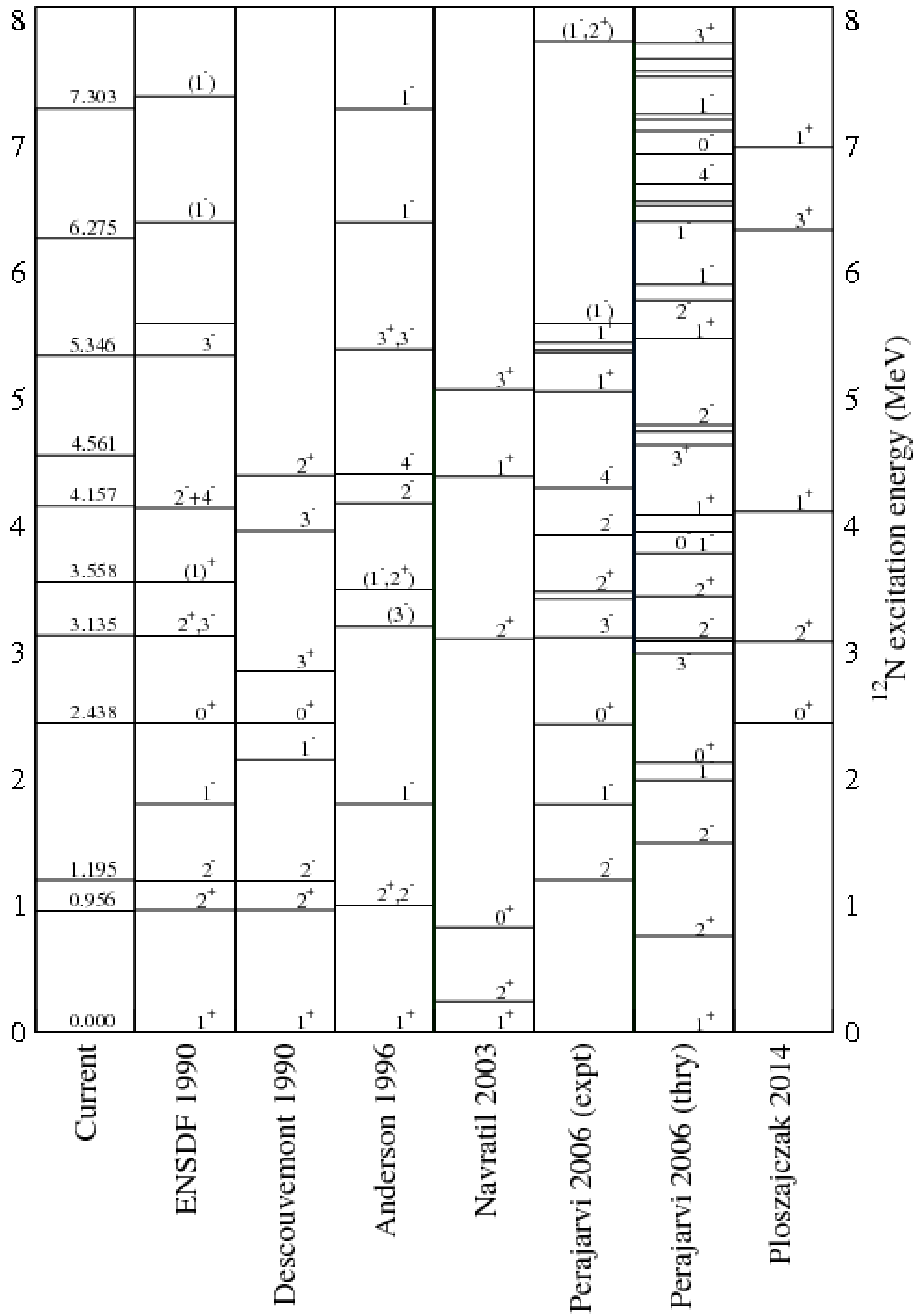

FIG. 4: Level diagram comparing the current work with compilation values, plus newer measurements and predictions. From left to right: current work; the ENSDF compilation [18]; predictions from a microscopic cluster study (Ref. [24]); data from a ^{12}C(p,n) measurement (Ref. [10]); NN+TNI predictions from Ab Initio 3-Body Interaction shell model calculations (Ref. [25]); ^{11}C(p,p) 0° data and OXBASH theoretical calculations (based on the shell model described in Ref. [26]) from Ref. [13]; and predictions from Continuum-Coupled shell model calculations (Ref. [27]). The lack of overall agreement is easily apparent.

served peak is a possible match; while coupling to the continuum shifts ^{12}N levels to smaller E_x values than in ^{12}B, there is also a 1^+ level predicted just above 4 MeV [27]. The OXBASH calculations from Ref. [13] suggest a 1^+ state near 4 MeV as well, as can be seen in Fig. 4; however, the authors of Ref. [13] do not assign a 1^+ level in this energy region. Also consistent with the L = 2 angular momentum transfer is a 2^+ predicted level at 4.40 MeV from a microscopic cluster study [24]. Within the sensitivity of the current work, we are unable to make a definitive assignment.

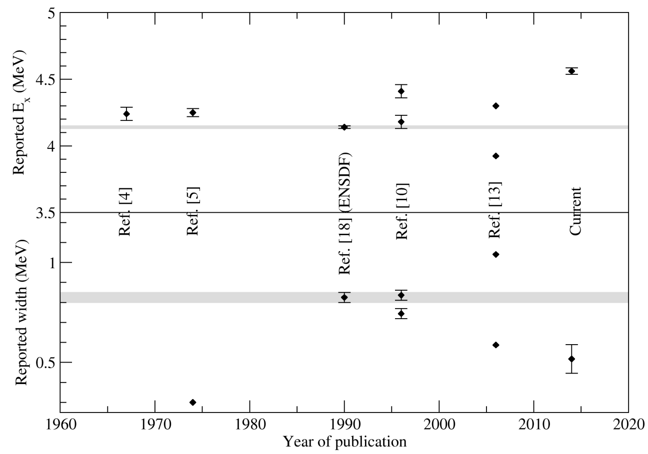

FIG. 5: (Color online) Comparison of the 4.561 MeV level with the literature.

D. 5 to 6 MeV

The measured width for the 5.348 MeV level in the current work is approximately twice the reported compilation value [18]; the $J^\pi = 3^-$ assignment is also incompatible with our derived L value. Ref. [10] placed this level at 5.40 ± 0.05 MeV with a width of 0.385 ± 0.055 MeV, in better agreement with our current width[1]. Shell model calculations using OXBASH [13] predict a 1^+ state around 5.48 MeV, the second 3^- instead falling nearer to 4.8 MeV (see Fig. 4); that work also seems to demonstrate a degenerate pair of levels with spin/parities of 3^+ and 3^- in this region, making 3^+ another possible assignment. The measured L = 2 transfer would be compatible with J = 1, 2, or 3, all positive parity states; however, there are no 2^+ levels currently predicted in this excitation energy region.

E. >6 MeV

For the level at 6.40 MeV [8, 9, 18], the centroid of the peak in the current work, $E_x = 6.275 \pm 0.021$ MeV, is substantially lower than the compilation value. In addition, the experimental width from this work, $\sim$ 260 keV, is roughly a factor of five smaller than the compilation value of 1.2 MeV [8, 18]. One previous study [6] placed this level at 6.1 MeV with a width of 0.3 ± 0.1 MeV, much closer to the value from the current work. These discrepancies could potentially point to the measured $E_x = 6.275 \pm 0.021$ MeV peak being a new level in ^{12}N; it is also possible that the (p,t) reaction is selectively populating lower E_x levels within what is suspected to be a wide multiplet [18]. If the angular momentum transfer is taken to be predominantly L = 1, the current work is compatible with the compilation $J^\pi = 1^-$ assignment [18]. Assuming instead the angular distribution shows L = 2 transfer would make the Continuum-Coupled prediction of a 3^+ level here [27] the more likely assignment. While the width of the observed peak is narrower than the compilation value, it is still large enough to include multiple levels which could contribute to a mixture of measured L-transfer values. However, any strict assignment is difficult given the lack of both precise level information and reliable shell model predictions around this excitation energy for comparison.

F. Additional discussion

The preceding discussion on analogue states in ^{12}C and ^{12}B, as well as anticipated levels from theoretical calculations, also applies more broadly to the structure of ^{12}N as a whole. As Figure 4 demonstrates, there is still a dearth of clear experimental data on this nucleus which could be reliably used to pin down theoretical predictions and make mirror assignments.

It appears, then, that the state of our theoretical understanding of such light mass, weakly bound nuclei is currently not adequate to address the level structure found in ^{12}N, nor is the experimental situation clear. Further development of theoretical predictions, as well as continued experimental study, is highly encouraged.

IV. CONCLUSION

We have measured the ^{14}N(p,t)^{12}N transfer reaction for the first time, using a 300 psig jet of pure nitrogen from the JENSA gas jet target. Excitation energies, angular distributions, and relative differential cross sections are extracted for populated levels, including previously unobserved levels at $E_x = 4.561 \pm 0.024$ and potentially $E_x = 6.275 \pm 0.021$ MeV. However, assignments to isobaric analogues are hindered by conflicting literature values and a lack of consistent theoretical predictions. A lower limit on the total cross section to the ^{12}N ground state of 0.02 mbarns is estimated. This work demonstrates the capability of the JENSA gas jet target, as it makes possible detailed in-beam studies of a number of gaseous elements.

Acknowledgments

We are indebted to the staff of the Holifield Radioactive Ion Beam Facility (HRIBF), without whose dedication this work would not have been possible. The au-

[1] To examine whether this level is incorrectly assigned, we removed it from the calibration fit and determined that its resultant E_x shifted by < 5 keV. We therefore associate it with the known 5.348 MeV level in the compilation [18], though the spin/parity and width are inconsistent.

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[1] K.A. Chipps *et al.*, Nucl. Instr. and Methods A **763**, 553 (2014).
[2] S.D. Pain, AIP Advances **4**, 041015 (2014).
[3] K.Sugimoto, K.Nakai, K.Matuda, T.Minamisono, J. Phys. Soc. Japan **25**, 1258 (1968).
[4] G. C. Ball and J. Cerny, Phys. Rev. **177**, 1466 (1969), URL http://link.aps.org/doi/10.1103/PhysRev.177.1466.
[5] H. Fuchs, K. Grabisch, D. Hilscher, U. Jahnke, H. Kluge, T. Masterson, and H. Morgenstern, Nuclear Physics A **234**, 61 (1974), ISSN 0375-9474, URL http://www.sciencedirect.com/science/article/pii/0375947474903790.
[6] C. F. Maguire, D. L. Hendrie, D. K. Scott, J. Mahoney, and F. Ajzenberg-Selove, Phys. Rev. C **13**, 933 (1976), URL http://link.aps.org/doi/10.1103/PhysRevC.13.933.
[7] D. E. Alburger and A. M. Nathan, Phys. Rev. C **17**, 280 (1978), URL http://link.aps.org/doi/10.1103/PhysRevC.17.280.
[8] W. Sterrenburg, M. Harakeh, S. V. D. Werf, and A. V. D. Woude, Nuclear Physics A **405**, 109 (1983), ISSN 0375-9474, URL http://www.sciencedirect.com/science/article/pii/0375947483903263.
[9] M. Harakeh, H. Akimune, I. Daito, Y. Fujita, M. Fujiwara, M. Greenfield, T. Inomata, J. Jnecke, K. Katori, S. Nakayama, et al., Nuclear Physics A **577**, 57 (1994), ISSN 0375-9474, proceeding of the International Symposium on Spin-Isospin Responses and Weak Processes in Hadrons and Nuclei, URL http://www.sciencedirect.com/science/article/pii/0375947494908346.
[10] B.D. Anderson *et al.*, Phys. Rev. C **54**, 237 (1996).
[11] T. Inomata, H. Akimune, I. Daito, H. Ejiri, H. Fujimura, Y. Fujita, M. Fujiwara, M. N. Harakeh, K. Ishibashi, H. Kohri, et al., Phys. Rev. C **57**, 3153 (1998), URL http://link.aps.org/doi/10.1103/PhysRevC.57.3153.
[12] T. Teranishi, S. Kubono, S. Shimoura, M. Notani, Y. Yanagisawa, S. Michimasa, K. Ue, H. Iwasaki, M. Kurokawa, Y. Satou, et al., Physics Letters B **556**, 27 (2003), ISSN 0370-2693, URL http://www.sciencedirect.com/science/article/pii/S0370269303000984.
[13] K. Perajarvi *et al.*, Phys. Rev. C **74**, 024306 (2006).
[14] Z. Yong-Nan, Z. Dong-Mei, Y. Da-Qing, Z. Yi, F. Ping, M. Mihara, K. Matsuta, M. Fukuda, T. Minamisono, T. Suzuki, et al., Chinese Physics Letters **27**, 022102 (2010), URL http://stacks.iop.org/0256-307X/27/i=2/a=022102.
[15] D. W. Lee, J. Powell, K. Perjrvi, F. Q. Guo, D. M. Moltz, and J. Cerny, Journal of Physics G: Nuclear and Particle Physics **38**, 075201 (2011), URL http://stacks.iop.org/0954-3899/38/i=7/a=075201.
[16] M.F. Jager *et al.*, Phys. Rev. C **86**, 011304(R) (2012).
[17] L.G. Sobotka *et al.*, Phys. Rev. C **87**, 054329 (2013).
[18] F. Ajzenberg-Selove, Nuclear Physics A **506**, 1 (1990), ISSN 0375-9474, URL http://www.sciencedirect.com/science/article/pii/037594749090271M.
[19] *Experimental Unevaluated Nuclear Data List (XUNDL) database*, http://www.nndc.bnl.gov/ensdf/.
[20] D. W. Bardayan, J. C. Blackmon, W. Bradfield-Smith, C. R. Brune, A. E. Champagne, T. Davinson, B. A. Johnson, R. L. Kozub, C. S. Lee, R. Lewis, et al., Phys. Rev. C **63**, 065802 (2001), URL http://link.aps.org/doi/10.1103/PhysRevC.63.065802.
[21] K. A. Chipps, D. W. Bardayan, K. Y. Chae, J. A. Cizewski, R. L. Kozub, C. Matei, B. H. Moazen, C. D. Nesaraja, P. D. O'Malley, S. D. Pain, et al., Phys. Rev. C **86**, 014329 (2012), URL http://link.aps.org/doi/10.1103/PhysRevC.86.014329.
[22] P.D. Kunz, *DWUCK5 finite-range DWBA code*, http://spot.colorado.edu/kunz/DWBA.html.
[23] R.L. Kozub, L.A. Kull, and E. Kashy, Nuclear Physics A **99**, 540 (1967).
[24] P. Descouvemont and I. Baraffe, Nuclear Physics A **514**, 66 (1990), ISSN 0375-9474, URL http://www.sciencedirect.com/science/article/pii/037594749090332G.
[25] P. Navrátil and W. E. Ormand, Phys. Rev. C **68**, 034305 (2003), URL http://link.aps.org/doi/10.1103/PhysRevC.68.034305.
[26] E. K. Warburton and B. A. Brown, Phys. Rev. C **46**, 923 (1992), URL http://link.aps.org/doi/10.1103/PhysRevC.46.923.
[27] M. Ploszajczak and J. Okolowicz, private communication.
[28] F. Ajzenberg-Selove and C. Busch, Nuclear Physics A **336**, 1 (1980), ISSN 0375-9474, URL http://www.sciencedirect.com/science/article/pii/0375947480901335.
[29] F. Ajzenberg-Selove, Nuclear Physics A **248**, 1 (1975), ISSN 0375-9474, URL http://www.sciencedirect.com/science/article/pii/0375947475902110.