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Excited-state transition-rate measurements in ^{18}C

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Excited states in ^{18}C were populated by the one-proton knockout reaction of an intermediate energy radioactive ^{19}N beam. The lifetime of the first 2^+ state was measured with the Köln/NSCL plunger via the recoil distance method to be $\tau(2_1^+) = 22.4 \pm 0.9(\text{stat})^{+3.3}_{-2.2}(\text{syst})$ ps, which corresponds to a reduced quadrupole transition strength of $B(E2; 2_1^+ \rightarrow 0_1^+) = 3.64^{+0.15}_{-0.14}(\text{stat})^{+0.40}_{-0.47}(\text{syst})\ e^2\text{fm}^4$. In addition, an upper limit on the lifetime of a higher-lying state feeding the 2_1^+ state was measured to be $\tau < 4.6$ ps. The results are compared to large-scale *ab initio* no-core shell model calculations using two accurate nucleon-nucleon interactions and the importance-truncation scheme. The comparison provides strong evidence that the inclusion of three-body forces is needed to describe the low-lying excited-state properties of this $A = 18$ system.

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Radioactive nuclides far from the valley of beta stability exhibit a variety of unique properties. For nuclei with large neutron-proton asymmetries, an extended and decoupled distribution of valence neutrons may occur [1,2]. The emergence of neutron halo nuclei, with one or more weakly bound neutrons spatially detached from the nuclear core, lies at the extreme isospin limit of such decoupling [3]. Quantifying the changes in nuclear structure toward such exotic behavior at the drip line has been a major focus of nuclear physics in recent years.

The neutron-rich carbon isotopic chain provides an attractive testing ground to study the effects of increasing neutron excess. One- and two-neutron halo structures are exhibited by ^{19}C [4,5] and ^{22}C [6], respectively. Furthermore, recent measurements of reduced electric quadrupole transition strengths between the first excited 2^+ state and the 0^+ ground state, $B(E2; 2_1^+ \rightarrow 0_1^+)$, have demonstrated a nearly constant value for ^{16}C [7–9] and ^{18}C [7] with respect to that of ^{14}C despite a dramatic decrease in the first 2^+ state excitation energy, $E(2_1^+)$, from nearly 7.0 MeV for ^{14}C to less than 2.0 MeV for ^{16,18}C. This observation presents a deviation from general systematic trends of even-even nuclei where the $E(2_1^+)$ and $B(E2)$ are expected to be inversely proportional to one another [10]. Electromagnetic observables provide a nonintrusive probe for the investigation of changes in nuclear structure responsible for this departure from expectations. Hence, a systematic study of transition rates for $N = 10, 12, 14$ carbon isotopes via lifetime measurements following nucleon knockout reactions was conducted.

In this work, we present lifetime measurements of the first two excited states in neutron-rich ^{18}C via the recoil distance method (RDM) using the Köln/NSCL plunger [11]. The results for ^{16}C [9] and ^{20}C [12] are presented elsewhere. RDM lifetime measurements are sensitive and reliable model-independent probes of nuclear structure. In addition, precisely measured electromagnetic observables are important to ascertain the accuracy of theoretical models predicting the evolution of nuclear structure as a function of isospin. To this end, the results are compared to *ab initio* no-core shell model (NCSM) calculations for ^{18}C generated from a systematic theoretical study of neutron-rich carbon isotopes.

The measurements were performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A 120 MeV/nucleon ^{22}Ne^{10+} primary beam was accelerated by the coupled K500 and K1200 cyclotrons and impinged upon a 1763 mg/cm^2 ^{9}Be production target. From the resulting fragmentation reaction products, a ^{19}N radioactive secondary beam was selected by the A1900 Fragment Separator [13]. The momentum acceptance was set to 0.7% and a 300 mg/cm^2 Al energy degrading wedge was used to obtain better than 97% purity of the desired secondary beam. Remaining beam contaminants were distinguished from ^{19}N by their time of flight between two 1 mm thick plastic scintillators at the A1900 focal plane and the object position of the S800 Spectrograph [14].

The secondary beam was delivered with an energy of 72 MeV/nucleon and an average intensity of 2.7×10^5 pps to

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the Köln/NSCL plunger [15] at the S800 target position. States in ^{18}C were populated by the one-proton knockout reaction on a 196 mg/cm^2 ^{9}Be plunger target and the nuclei emerged with a velocity distribution centered at $\beta_{\text{fast}} = v/c = 0.3565(5)$. After a plunger-controlled flight distance, the ^{18}C nuclei were slowed in a 2010 mg/cm^2 ^{181}Ta plunger degrader to a final velocity distribution centered at $\beta_{\text{slow}} = 0.2920(5)$. Knockout reaction residues were identified on an event-by-event basis by their energy loss through the S800 ionization chamber [16] and time of flight between plastic scintillators at the object position and focal plane of the S800. Doppler-shifted de-excitation γ rays were measured with the Segmented Germanium Array (SeGA) [17] in coincidence with these reaction residues. In the plunger configuration, 15 SeGA detectors were centered around the plunger in two rings at laboratory angles of 30° and 140° with respect to the beam axis and fully instrumented with the Digital Data Acquisition System [18]. The particle-γ coincidence measurement between the S800 and SeGA significantly reduced background contaminants in the γ-ray spectra. Software particle gates implemented during the analysis on both the incoming ^{19}N and outgoing ^{18}C beam components provided further background suppression.

Data were taken with only the plunger target installed to examine relative state population. Two known transitions in ^{18}C were observed with energies of 932(11) and 1585(19) keV, in agreement with the values of 919(10) and 1585(10) keV reported in Ref. [19]. The γ-ray energy spectra for the 30° and 140° rings of SeGA are plotted in Fig. 1. There, the Doppler corrections were performed to align the 1585 keV photopeaks originating from decays downstream of the target. The misalignment of the 932 keV photopeaks illustrated by the dashed line is removed by Doppler correcting with a beam velocity $\beta = 0.3650(5) > \beta_{\text{fast}}$. Hence, the majority of these γ-ray decays occurred inside the target, indicating a lifetime shorter than ≈5 ps (assuming a midtarget reaction). The 1585 keV de-excitation corresponds to the $2_1^+ \to 0_1^+$ transition and the 932 keV transition is known to populate the 2_1^+ level from a higher-lying state of undetermined J^π [7,19]. For the purpose of discussion, this state shall be denoted by $J^\pi = 2_2^+$ as favored by both the *ab initio* theoretical calculations

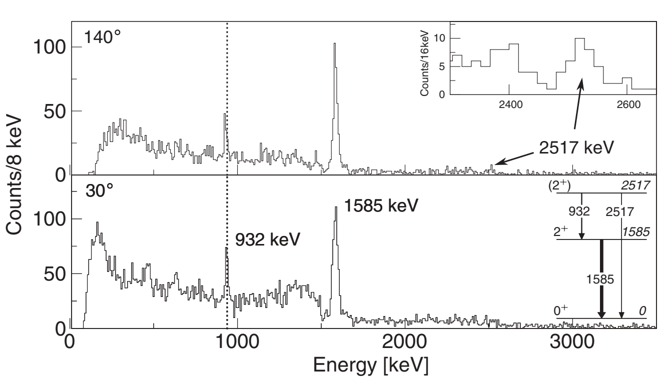

FIG. 1. ^{18}C-gated and Doppler-corrected γ-ray energy spectra for the 30° and 140° rings of SeGA collected prior to installing the plunger degrader. The arrow widths of the inset level scheme are representative of the transition relative intensities measured after in-beam efficiency corrections.

discussed below and by shell model calculations [19] using the WBT interaction [20]. In addition, a small enhancement above background was observed at 2517(30) keV corresponding to the $2_2^+ \to 0_1^+$ transition. A level scheme of the observed transitions is presented as an inset in Fig. 1.

After in-beam efficiency corrections at Doppler-shifted laboratory energies and assuming no additional feeding contributions to either observed state, the proton knockout reaction was found to preferentially populate the 2_1^+ state by a ratio of 4 : 1. Thus only 20% of the total photopeak intensity was shared between the $2_2^+ \to 2_1^+$ and $2_2^+ \to 0_1^+$ transitions. The branching ratios were determined to be 86(12)% and 14(12)%, respectively, by summing all experimental γ-ray spectra in the 140° ring of SeGA for enhanced statistics. The 30° ring data were not used as the 2517 keV transition was Doppler shifted to over 3.3 MeV where the photopeak efficiency was not measured. The small production cross section and the anticipated short lifetime of the 2_2^+ state rendered feeding corrections for the 2_1^+ state unnecessary.

^{18}C-gated γ-ray spectra were collected at five target-degrader distances of 0.0, 0.6, 1.5, 2.2, and 3.0 mm. Each distance yielded unique γ-ray line shapes with components from fast, slowing, and fully slowed excited-state ^{18}C nuclei that decayed before, inside, and after the plunger degrader. Fitting these experimental spectra with simulated γ-ray line shapes generated with various input lifetime values and applying a χ^2 goodness of fit test yielded the measured lifetime result. The line-shape simulation procedure and statistical analysis were carried out within the GEANT4 [21] and ROOT [22] toolkits and are similar to the method reported in Ref. [23]. Obtaining accurate simulated γ-ray line shapes required the parametrization of all pertinent experimental details. In particular, the simulations accurately reproduced the geometry of the experimental setup and were able to describe the phase space of the incoming secondary beam, the proton knockout kinematics and subsequent energy and angular straggling of the ^{18}C nuclei, and the γ-ray decay and detection processes—including the Doppler broadening of the detected photopeaks, the Lorentz-boosted γ-ray intensity distribution asymmetry, the detector response, and the γ-ray detection efficiency.

After the simulation parameters were systematically fixed to properly characterize the experimental setup, γ-ray spectra were produced over a coarse lifetime range and fit to the 30° and 140° ring experimental data at each target-degrader distance. To properly account for the unique γ-ray background present in each ring and at each distance, the coefficients of a linear background were allowed to vary freely in the fit. For each input lifetime, the χ^2 values of all ten fits were summed and the optimal set of background parameters was taken from fits at the minimum of the resulting distribution. With the background parameters fixed, a final lifetime scan was performed in 1 ps increments around the coarse lifetime scan minimum. A freely varying normalization factor accounted for the different statistics obtained in each ring and at each distance. A distribution of summed χ^2 values was constructed from all of the fits and from the minimum a lifetime of 22.4 ± 0.9(stat) ps was extracted. Figure 2 demonstrates the resulting best fit of simulated line shapes to the experimental γ-ray spectra at this lifetime minimum. In accord with previous

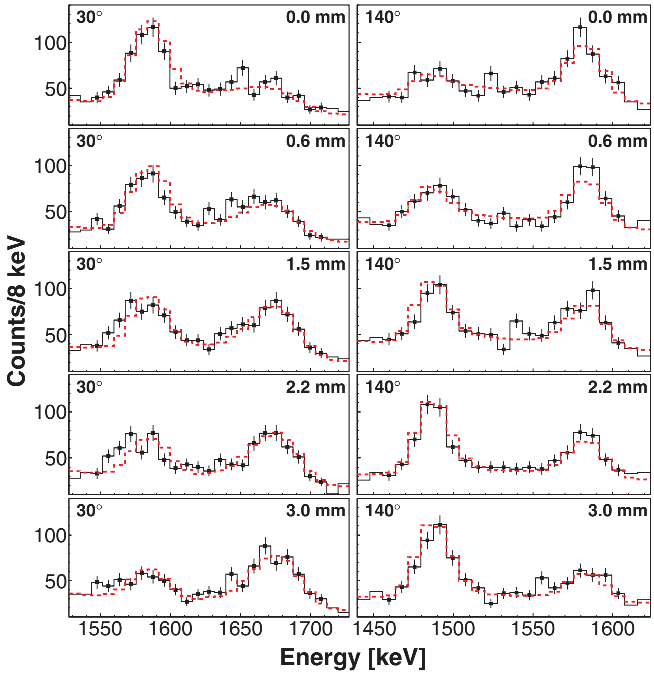

FIG. 2. (Color online) Experimental γ-ray spectra with statistical uncertainties (solid black) and simulated line shapes (dashed red) generated with the best-fit lifetime $\tau = 22.4$ ps for the 1585 keV transition in ^{18}C for the 30° and 140° rings of SeGA and all five target-degrader distances. Doppler corrections were done with $\beta_{\text{slow}} = 0.2920$.

Köln/NSCL plunger lifetime analyses using γ-ray line-shape simulations [23–25], only the spectral features most sensitive to lifetime effects—namely the Doppler-shifted photopeaks and their relative centroid amplitudes—were included in the lifetime χ^2 analysis as indicated by the experimental error bars in Fig. 2.

RDM lifetime measurements at NSCL use radioactive secondary beams with sufficient energy to undergo nucleon knockout reactions on the plunger degrader after passing unreacted through the target. The uncertainty in the ratio of knockout reactions producing ^{18}C on the target and degrader, $R = N_{\text{tar}}/N_{\text{deg}}$, comprised the most dominant source of systematic error in the reported measurement. To constrain R, a two-dimensional χ^2 hypersurface was constructed from the fit of experimental spectra to simulated line shapes generated with various input lifetimes and reaction ratios. A bivariate quadratic function was fit to this hypersurface and both the global minimum and the one-sigma ellipse tracing the function at a value of min + 1 were obtained. By projecting the minimum and ellipse onto the reaction ratio axis, the ratio was determined to be $R = 2.15 \pm 0.74$. An additional constraint on the ratio was determined by assuming the slow component observed in the γ-ray spectrum at the 3.0 mm distance strictly arose from reactions on the degrader. Since this distance is insufficient to preclude target reactions from contributing to the slow peak, the reaction ratio determined by integrating the two photopeaks sets an absolute lower limit of $R = 1.81$. Thus the final reaction ratio was taken to be $R = 2.15^{+0.74}_{-0.34}$.

TABLE I. Measured properties of ^{18}C excited states.

Observable	Experiment	Unit
$E(2_1^+ \rightarrow 0_1^+)$	1585(19)	keV
$E(2_2^+ \rightarrow 0_1^+)$	2517(30)	keV
$E(2_2^+ \rightarrow 2_1^+)$	932(11)	keV
$BR(2_2^+ \rightarrow 0_1^+)$	14(12)	%
$BR(2_2^+ \rightarrow 2_1^+)$	86(12)	%
$\tau(2_1^+)$	22.4±0.9(stat)$^{+3.3}_{-2.2}$(syst)	ps
$\tau(2_2^+)$	<4.6	ps
$B(E2; 2_1^+ \rightarrow 0_1^+)$	3.64$^{+0.15}_{-0.14}$(stat)$^{+0.40}_{-0.47}$(syst)	e^{2}fm^4

To ascertain the measurement error introduced by the uncertainty in R, two separate lifetime scans were performed using the upper and lower limits of the ratio. From the minima of the distribution of summed χ^2 values of the fits, a systematic error on the lifetime of $^{+2.2}_{-1.1}$ ps was extracted. In addition, deviations between the experimental and simulated ^{18}C momentum distributions were found to be an important source of systematic error as they impact the simulated γ-ray spectra. In particular, a 2% change in the degrader thickness was tolerable before disrupting the fit of the experimental and simulated spectra. Another pair of lifetime scans were performed at these degrader thickness extrema and resulted in an additional systematic uncertainty of ± 1.1 ps. Other sources of error were found to be negligible.

Adding these two systematic errors, the measured lifetime of the 2_1^+ state in ^{18}C was found to be $\tau(2_1^+) = 22.4 \pm 0.9(\text{stat})^{+3.3}_{-2.2}(\text{syst})$ ps and is in good agreement with the reported lifetime of $18.9 \pm 0.9(\text{stat}) \pm 4.4(\text{syst})$ ps from Ref. [7]. This result corresponds to a reduced quadrupole transition strength of $B(E2; 2_1^+ \rightarrow 0_1^+) = 3.64^{+0.15}_{-0.14}(\text{stat})^{+0.40}_{-0.47}(\text{syst})$ e^2 fm^4. Table I summarizes these measured excited-state properties in ^{18}C.

In addition, a lifetime upper limit for the 2_2^+ state has been established by line-shape analysis of the 932 keV $2_2^+ \rightarrow 2_1^+$ transition. The combination of a thick plunger target and degrader (optimized for the measurement of lifetimes on the order of 20 ps) and a fast de-excitation (as discussed above) resulted in the majority of γ-ray decays proceeding within the same material where the knockout reaction occurred. With very few decays in vacuum, the Doppler-corrected line shapes were qualitatively the same regardless of target-degrader distance. Thus all five experimental γ-ray spectra were summed to smooth the statistical fluctuations in the background. The resulting summed spectra for each ring were fit with simulated line shapes generated with various input lifetimes and the reaction ratio $R = 2.15$ determined from analysis of the $2_1^+ \rightarrow 0_1^+$ transition. From the minimum of the summed 30° and 140° ring distributions of χ^2 values, a lifetime of $\tau(2_2^+) = 3.2 \pm 0.7$ ps was extracted. Figure 3 illustrates the fit of simulated line shapes to the experimental γ-ray spectra at this lifetime. Given the limited experimental sensitivity to such short lifetimes—evidenced by the large fractional uncertainty—and the low statistics, we conservatively quote the lifetime as a two-sigma upper limit, $\tau(2_2^+) < 4.6$ ps.

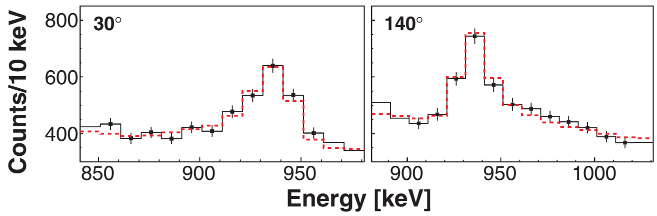

FIG. 3. (Color online) Summed experimental γ-ray spectra with statistical uncertainties (solid black) and simulated line shapes (dashed red) generated with the best-fit lifetime $\tau(2_2^+) = 3.2$ ps for the 932 keV transition in ^{18}C. As in Fig. 2, bins with experimental error bars indicate the region where the statistical analysis was carried out.

The measured electromagnetic observables provide a precise testing ground near the computational limits for *ab initio*-type calculations for this relatively heavy $A = 18$ system. Hence, the results are compared with large-scale *ab initio* no-core shell model [26,27] calculations employing two accurate and very different NN interactions: CD-Bonn 2000 (CDB2K) [28], which is based on one-boson exchange theory, and INOY [29] that introduces a nonlocality in the two-body potential to include some effects of three-nucleon forces and is fit to three-nucleon observables. NCSM calculations for low-lying states of even-even carbon isotopes have been performed and a detailed overview of the systematics of the 2^+ states has recently been presented in Ref. [30]. A more direct discussion for the case of ^{18}C is given below.

The calculations were performed using a harmonic-oscillator (HO) basis truncated by a total HO energy cutoff, characterized by the maximal number of HO excitations, $N_{\max}$, above the unperturbed ground state. Due to the strong short-range correlations generated by the NN potentials, effective interactions must be calculated to speed up convergence; those appropriate to the basis truncations were derived by performing unitary transformations in the two-nucleon HO basis. The results exhibit a dependence on $N_{\max}$ and the HO frequency, $\hbar\Omega$, that should disappear once complete convergence is reached. This implies that $N_{\max}$ sequences obtained with different $\hbar\Omega$ should all converge to the same results and a constrained fit can be applied to multiple sequences in order to extrapolate the infinite, untruncated model space result [30,31]. It is therefore advantageous to use the largest $N_{\max}$ basis feasible over a wide $\hbar\Omega$ range. As the current limit on full space ^{18}C calculations is $N_{\max} = 6$ (with a dimension of 1.4×10^9), the recently introduced importance-truncated no-core shell model (IT-NCSM) scheme [32,33] was employed. Within this scheme, basis states that are irrelevant for the description of the ground state and low-lying states are identified via many-body perturbation theory and excluded from the calculation. Important basis states remain to preserve the predictive power, but the dimension of the matrix eigenvalue problem is reduced. The IT-NCSM extends the calculations of this heavy $A = 18$ system to $N_{\max} = 8$ and improves the reliability of the extrapolated calculations. Figure 4 presents the constrained fits of the calculated $B(E2; 2_1^+ \to 0_1^+)$ and $Q(2_1^+)$ values over various $\hbar\Omega$ as a function of $1/N_{\max}$. Plotted in this manner, the infinite model space results correspond to $1/N_{\max} \to 0$.

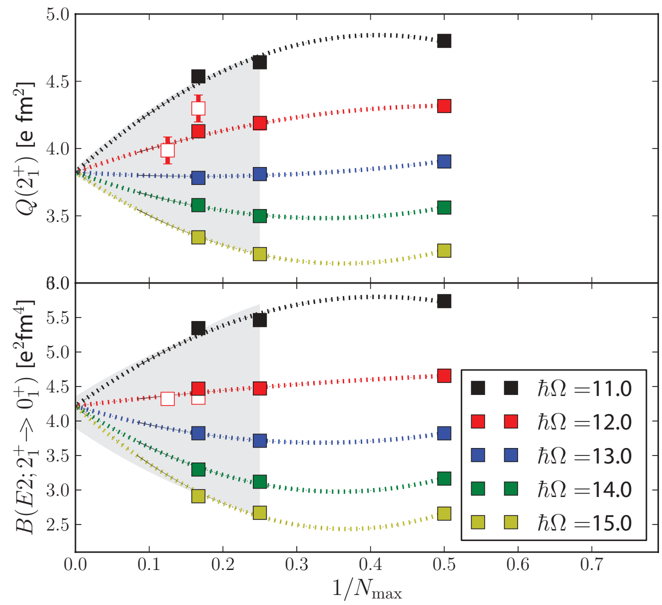

FIG. 4. (Color online) Select *ab initio* NCSM results with the CDB2K interaction. Filled symbols correspond to full space results. Open symbols illustrate the importance-truncated scheme results for $N_{\max} = 6, 8$ at $\hbar\Omega = 12$. Each extrapolation curve corresponds to the sequence of results obtained at a fixed $\hbar\Omega$ value. The gray bounded regions were constructed by removing the two lowest (highest) $\hbar\Omega$ sequences from the constrained fit to produce upper (lower) limits as an estimate of the uncertainty.

The experimental and extrapolated theoretical results for the excitation energy, transition strengths, and quadrupole moment, $Q(2^+)$, of the first two excited states in ^{18}C are presented in Table II. It should be stressed that no effective charges or other adjustable parameters were used in the calculations and that the final results were obtained using a

TABLE II. *Ab initio* NCSM results for the 2_1^+ state in ^{14,18}C and the 2_2^+ state in ^{18}C. Experimental results are taken from this work for ^{18}C and from Ref. [10] for ^{14}C. Excitation energies are in units of MeV while $B(E2)$, $B(M1)$, and Q values are in units of e^2 fm^4, μ_N^2, and efm^2, respectively.

Nucleus	Observable	Experiment	CDB2K	INOY[a]
^{18}C	$E(2_1^+)$	1.585(19)	1.8(1)	1.6(2)
^{18}C	$B(E2; 2_1^+ \to 0_1^+)$	$3.64^{+0.55}_{-0.61}$	4.2(4)	1.5(−)
^{18}C	$Q(2_1^+)$		+3.8(4)	−0.5(−)
^{18}C	$E(2_2^+)$	2.517(30)	3.6(4)	2.0(2)
^{18}C	$B(E2; 2_2^+ \to 0_1^+)$		0.18(3)	0.3(−)
^{18}C	$B(E2; 2_2^+ \to 2_1^+)$		0.13(6)	1.9(−)
^{18}C	$B(M1; 2_2^+ \to 2_1^+)$		0.03(1)	0.06(−)
^{18}C	$Q(2_2^+)$		−3.2(6)	+0.2(−)
^{14}C	$E(2_1^+)$	7.012(4)	5.4(8)	8.8(5)
^{14}C	$B(E2; 2_1^+ \to 0_1^+)$	3.7(5)	5.3(5)	3.5(2)
^{14}C	$Q(2_1^+)$		+4.7(3)	+3.7(2)

[a]We observed a strong dependence on the choice of $\hbar\Omega$ due to mixing between the two 2^+ states in ^{18}C. The uncertainty estimation of some observables is therefore challenging.

range of $\hbar\Omega$ values. Convergence of the 2_2^+ state is difficult; for this state our results are not extrapolations, but based upon calculations performed at $\hbar\Omega = 11, 12, 13$ MeV and 17, 18, 19 MeV for CDB2K and INOY, respectively. At the same time we check the predictive power and consistency of our calculations by comparing our ^{14}C results to experimental data [10]. The excitation mechanisms of the 2^+ states in ^{14,18}C are predicted to be quite different [30]. From the results presented in Table II it is clear that the ^{14}C excitation energy comes out a bit low and the calculated $B(E2)$ somewhat high with the CDB2K interaction. The INOY interaction overestimates the $E(2^+)$ of ^{14}C while producing a $B(E2)$ value consistent with the experimental data.

It is interesting to compare the ^{18}C results obtained from CDB2K with those from INOY as this can reveal a possible sensitivity of certain observables to three-nucleon force effects. Indeed, recent experimental [9] and theoretical [30] work for ^{16}C have demonstrated such a sensitivity for electromagnetic observables of states above the first 2^+. A similar endeavor for ^{18}C is more difficult as the INOY interaction gives a small splitting of the two 2^+ states and the mixing between these two results in large uncertainties. Nonetheless several conclusions are drawn. Particularly striking features observed with the INOY interaction are the possible negative quadrupole moment of the 2_1^+ state and the relatively strong $B(E2)$ strength for the $2_2^+ \to 2_1^+$ transition. In contrast, the corresponding quadrupole moment was found to be large and positive and the $B(E2; 2_2^+ \to 2_1^+)$ an order of magnitude smaller when using the CDB2K interaction. We note that the preliminary results of initial calculations using chiral two- and three-nucleon interactions show similarity to the present INOY results concerning the quadrupole moment signs and the transitions from the 2_2^+ state.

The 2_1^+ excitation energies obtained from both interactions agree well with the experimental results. The $B(E2; 2_1^+ \to 0_1^+) = 4.2(4)$ e^2 fm^4 calculated with CDB2K compares well with the experimental value $3.64^{+0.55}_{-0.61}$ e^2 fm^4 while the INOY results are too small. This is not surprising as the INOY interaction generates an anomalously large nuclear density, which generally leads to the underprediction of size-dependent observables. In addition, from the calculated 2_2^+ transition strengths and excitation energies, branching ratios for the $2_2^+ \to 2_1^+$ transition of 96% and 85% were deduced with the CDB2K and INOY interactions, respectively. The measured central value of 86% therefore demonstrates a preference for the INOY result. The extracted $B(E2; 2_2^+ \to 0_1^+)$ lower limit from the $\tau(2_2^+)$ upper limit of 0.25 e^2 fm^4 also favors the INOY interaction over the CDB2K. No conclusion is drawn from comparisons of the $2_2^+ \to 2_1^+$ transition strengths as the $M1$ transition dominates both calculations. The overall preference of the INOY potential, which includes some three-body force effects, together with the preliminary results using chiral two- and three-body interactions, points to the necessity of three-body interactions for obtaining a proper description of ^{18}C and, as similar effects were found in ^{16}C [9,30], of the neutron-rich nuclei in this mass region.

In summary, electromagnetic observables were measured for the first two excited states in neutron-rich ^{18}C. A lifetime of $\tau(2_1^+) = 22.4 \pm 0.9(\text{stat})^{+3.3}_{-2.2}(\text{syst})$ ps was measured with the recoil distance method following a one-proton knockout of ^{19}N in inverse kinematics and is in good agreement with the previous measurement [7] while significantly reducing the uncertainty. In addition, a lifetime upper limit of $\tau(2_2^+) <$ 4.6 ps was measured for the state that has been denoted in this work as the second 2^+ as predicted by theory. The resulting $B(E2)$ transition strengths, measured excitation energies, and branching ratios have been compared to large-scale *ab initio* NCSM calculations using accurate NN interactions and utilizing the importance-truncation scheme to increase the predictive power of this heavy $A = 18$ system. While the CDB2K interaction, with its more realistic description of the nuclear density, accurately reproduces the measured $B(E2; 2_1^+ \to 0_1^+)$, we find several observables from the 2_2^+ state which demonstrate a preference for the INOY interaction, including the excitation energy, the branching ratios, and the $2_2^+ \to 0_1^+$ transition strength. These additional observables provide strong evidence for the need to include three-nucleon forces to attain better descriptive power. Future measurements of the diagonal matrix elements of the 2^+ states would be of great interest. In particular, magnetic moment calculations converge faster than their quadrupole moment counterparts and offer additional sensitivity to the two- and three-body details of the nuclear interaction.

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