^{15}C(d, p)^{16}C Reaction and Exotic Behavior in ^{16}C

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We have studied the ^{15}C(d, p)^{16}C reaction in inverse kinematics using the Helical Orbit Spectrometer at Argonne National Laboratory. Prior studies of electromagnetic-transition rates in ^{16}C suggested an exotic decoupling of the valence neutrons from the core in that nucleus. Neutron-adding spectroscopic factors give a different probe of the wave functions of the relevant states in ^{16}C. Shell-model calculations reproduce both the present transfer data and the previously measured transition rates, suggesting that ^{16}C may be described without invoking very exotic phenomena.

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An important question in the study of atomic nuclei with a large neutron excess is how they behave differently from stable nuclei. As one widely noted example, recent measurements [1–3] of the matrix elements for the electromagnetic decay of the 2_1^+ state in the neutron-rich isotopes of C with $A \geq 16$ found the surprising result that $B(E2)$ values for the $2_1^+ \rightarrow 0_1^+$ transitions were much smaller than expectations based on trends from stable nuclei. Particularly for ^{16}C, when combined with other inelastic-scattering data [2,4,5], the results implied an unexpectedly large ratio of proton-to-neutron transition amplitudes M_p/M_n and were interpreted as an "anomalous" or "unusual" decoupling of the sd-shell valence neutrons from the ^{14}C core [1,2]. This suggestion spurred many theoretical studies using the shell-model [6–8], three-body calculations [9–11], and cluster models [12,13]. While these models used rather different physical approaches, and made different predictions about other properties of ^{16}C, most reproduced the reported small value of the $B(E2)$ for the $2_1^+ \rightarrow 0_1^+$ transition and supported a conclusion that ^{16}C is anomalous when compared to stable nuclei.

Later measurements [14] on ^{16}C using a similar technique as employed in Ref. [1] found a $B(E2)$ that was larger than those reported in Refs. [1,2] but which was still smaller than that expected from systematics in this mass region. A recent lifetime measurement for the first-excited state in ^{16}C [15], however, reported a much larger $B(E2)$, in line with systematic values and requiring no exotic interpretation. In an attempt to clarify this situation, we have used a qualitatively different experimental probe, the (d, p) neutron-transfer reaction, to obtain information about the low-lying states in ^{16}C complementary to that provided by electromagnetic transitions. The single-particle strengths from (d, p) constrain the wave functions of these states and test directly the various theoretical descriptions of ^{16}C and the notion of exotic behavior. We find that the neutron-transfer and the most recent electromagnetic-transition data can both be accommodated by the same shell-model calculations, calling into question the suggestion that ^{16}C exhibits exotic, unexpected behavior.

Studies of the ^{14}C(d, p)^{15}C reaction [16] indicate that the ground state of ^{15}C is well described as a $1s_{1/2}$ neutron in a single-particle state around ^{14}C. Also, in C nuclei, it is known from studies of the (d, ^{3}He) reaction [17] that the occupancy of the $0p_{1/2}$ orbit by protons decreases as the neutron number increases, a trend that may continue to heavier C isotopes. The 8 neutrons in ^{14}C filling the p shell should produce a stable core, and ^{16}C is thus ideal for studying two-neutron interactions in the sd shell. The relative neutron-adding spectroscopic factors reflect the distribution of the $\nu(1s_{1/2})^2$ component of 0^+ states and the $\nu(1s_{1/2}0d_{5/2})$ component of 2^+ and 3^+ states. This information can also be used to deduce some of the matrix elements of the $\nu(sd)^2$ residual interaction, which can be compared to those for the corresponding states in ^{18}O, where the $1s_{1/2}$ and $0d_{5/2}$ orbitals are inverted as known from the ground-state spins of ^{15}C($J^{\pi}_{\mathrm{g.s.}} = 1/2^+$) and ^{17}O($J^{\pi}_{\mathrm{g.s.}} = 5/2^+$). Fortune *et al.* [18] used the matrix elements derived by a similar procedure from ^{18}O (Ref. [19], referred to as "LSF") to calculate wave functions and excitation energies for two-neutron states observed in the ^{14}C(t, p)^{16}C reaction. With single-neutron adding, we can test those wave functions, as well as those obtained from shell-model and other calculations.

We have studied the ^{15}C$(d, p)^{16}$C reaction in inverse kinematics using a beam of short-lived ($T_{1/2} = 2.45$ s) ^{15}C ions from the In-Flight facility at ATLAS at Argonne National Laboratory [20]. The beam was produced by bombarding a cryogenic D_2 gas cell with a 100 pnA ^{14}C primary beam with an energy of 133 MeV. The resulting ^{15}C beam, from the ^{14}C$(d, p)^{15}$C reaction, had an energy of 123 MeV, corresponding to a deuteron energy of 16.4 MeV, where the (d, p) reaction is well understood. The intensity ranged from 1 to 2×10^6 ^{15}C per second.

Protons from the ^{15}C$(d, p)^{16}$C reaction were detected with the Helical Orbit Spectrometer (HELIOS) [21,22]. HELIOS is a new device designed to study reactions in inverse kinematics. It consists of a large-bore, superconducting solenoid with its axis aligned with the beam direction. The magnetic field was 2.85 T, and a 110 μg/cm^2 deuterated polyethelyne $[(C_2D_4)_n]$ target was used. Protons emitted at forward angles in the center-of-mass frame ($\theta_{\mathrm{lab}} > 90°$) were transported in the magnetic field and detected with a position-sensitive silicon-detector array surrounding the beam axis upstream of the target. The silicon-detector array measured the protons' energy, distance z from the target, and flight time (equal to the cyclotron period $T_{\mathrm{cyc}} = 2\pi m/Bq$). The recoiling ^{16}C ions were detected in coincidence with protons in an array of silicon-detector $\Delta E - E$ telescopes that covered 0.5°–2.8° in the laboratory. All events with a particle detected in the upstream silicon array were recorded. The beam intensity was monitored by using a silicon detector placed at 0° behind a mesh attenuator that reduced the beam flux by a factor of 1000. The widely spaced holes in this attenuator made this measurement sensitive to the alignment and the shape of the beam spot, giving an estimated 30% systematic uncertainty for the absolute beam flux.

Figure 1(a) shows a spectrum of proton energy versus position z from the ^{15}C$(d, p)^{16}$C reaction for p-^{16}C coincidence events. The diagonal lines correspond to different excited states in ^{16}C, and the excitation-energy spectrum derived from these data is shown in Fig. 1(b). The resolution is approximately 140 keV FWHM, determined by a combination of intrinsic detector resolution, energy loss of the beam in the target, and the energy spread of the beam from straggling in the production cell and the kinematics of the production reaction. This resolution was insufficient to resolve the closely spaced $2_2^+/3_1^+$ doublet near $E_X(^{16}\mathrm{C}) = 4$ MeV, though the width of this peak is 20% greater than those of the other three excitations.

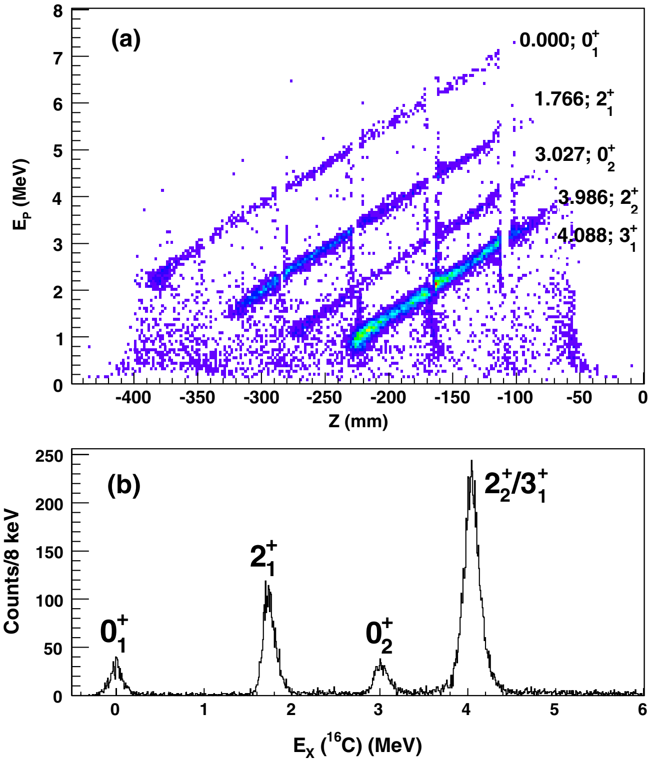

FIG. 1 (color online). (a) Proton energy versus position spectrum for the ^{15}C$(d, p)^{16}$C reaction measured in inverse kinematics with HELIOS. The target is at $z = 0$ mm, and z increases in the beam direction. The different groups correspond to different final states in ^{16}C, as is indicated on the figure. (b) ^{16}C excitation-energy spectrum.

Angular distributions for the three resolved transitions in ^{16}C and the unresolved $2_2^+/3_1^+$ doublet are shown in Fig. 2. The proton solid angle was defined by the geometry of the upstream silicon-detector array. The efficiency for the coincident proton-^{16}C-recoil detection was calculated by using Monte Carlo simulations of particle transport in HELIOS as described in Ref. [21] with the measured field map of the solenoid magnet. This efficiency was typically 80%, with an estimated 5% systematic uncertainty from detector misalignment. The absolute cross-section scale was determined by using the 0° monitor detector as described above; the plotted uncertainties reflect only the combined statistical uncertainties from the data and Monte Carlo simulations. The horizontal bars represent the angular range included in each data point. The angular distributions for the ground and second-excited states show clear $\ell = 0$ character, confirming the tentative assignment of $J^\pi = 0^+$ [23] for the second-excited state. The first-excited state and the presumed doublet near 4 MeV are consistent with $\ell = 2$.

Relative spectroscopic factors were obtained by comparing the experimental cross sections with distorted-wave Born approximation calculations done with the code PTOLEMY [24]. The curves in Fig. 2 represent calculations done with four sets of optical-model parameters, and each curve was normalized to the experimental cross sections. The deduced spectroscopic factors are listed in Table I. Because of the uncertainty in the absolute cross sections, the results were normalized by requiring the sum of the 0^+ spectroscopic factors to add up to 2.0. The values obtained with each of the four parameters sets were averaged to obtain the results in Table I. The errors are dominated by

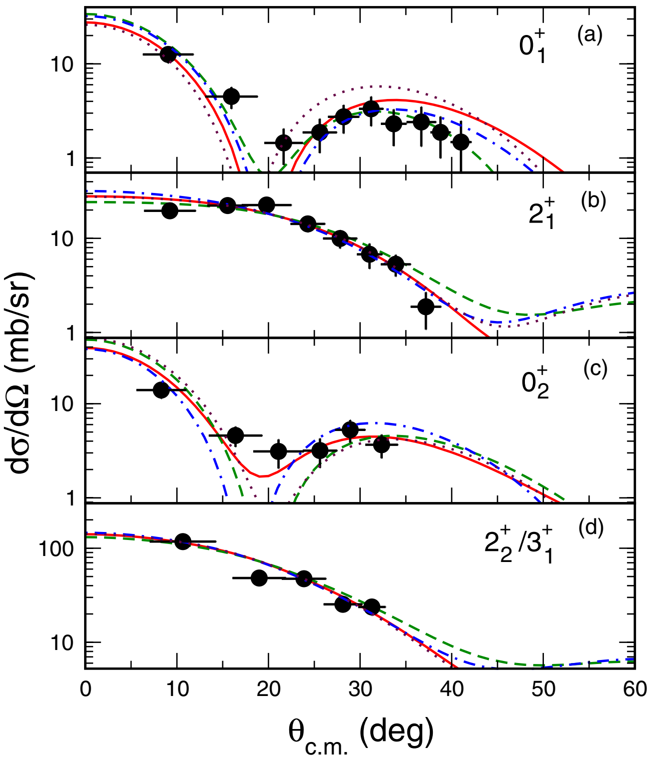

FIG. 2 (color online). Angular distributions for different transitions in $^{15}C(d,p)^{16}C$. The curves represent distorted-wave Born approximation calculations described in the text, using optical-model parameters from Refs. [27] (solid line), [28] (dashed line), [29] (dot-dashed line), and [30] (dotted line). The cross-section uncertainties are statistical and do not reflect systematic errors in the absolute scale, as described in the text.

our estimate of the uncertainties from the normalization and the variations among the different parameter sets. While the 2_2^+ and 3_1^+ states could not be resolved, their relative contributions could be estimated from the widths of the lower excitations (0.140 MeV FWHM) and the centroid of the doublet peak, 4.077(.005) MeV. The estimated maximum possible contribution to this doublet from the 2_2^+ state is 23%. This limit is used to derive the maximum spectroscopic factor for the 2_2^+ state and the allowed range of values for the 3_1^+ state consistent with that limit as given in Table I.

The excitation energies and spectroscopic factors obtained from the LSF wave functions, and from shell-model calculations using the Warburton-Brown (WBP) interaction [25], also appear in Table I; this interaction was used in Ref. [3] to reproduce the $2_1^+ \rightarrow 0_1^+$ transition data for several neutron-rich C isotopes. The present data for the three lowest states in ^{16}C are in good agreement with the WBP calculations. The estimated values for the 2_2^+ and 3_1^+ levels are also consistent with shell-model predictions.

The strength of both 0^+ states in the (d,p) reaction indicates that each has a substantial $(1s_{1/2})^2$ component, revealing strong mixing between the $(1s_{1/2})^2$ and $(0d_{5/2})^2$ configurations. Also, while in ^{15}C the $1/2^+$ ground state may be identified with the $1s_{1/2}$ configuration, and the 0.74 MeV $5/2^+$ state with the $0d_{5/2}$ one, in ^{16}C the $(1s_{1/2})^2$ configuration is dominant in the excited 0^+ level. This result agrees qualitatively with those of Ref. [11], although the predicted configuration mixing between the two 0^+ states is less than what is observed. Other calculations [6,10] give even larger mixing; in Ref. [10] the $(1s_{1/2})^2$ is larger in the ground state, and in Ref. [6] the two configurations carry approximately equal amplitudes. The observed mixing also conflicts with the conclusions of Ref. [2] that the ground state is dominantly $(1s_{1/2})^2$ and that the first-excited level is largely a single-neutron $(1s_{1/2}0d_{5/2})$ excitation. Our spectroscopic factor for the 2_1^+ excitation agrees with the strongly configuration-mixed wave functions of the LSF and WBP shell-model analyses.

The measured spectroscopic factors, excitation energies, and the energies of the $1s_{1/2}$ and $0d_{5/2}$ levels from ^{15}C yield matrix elements for the $\nu(sd)^2$ residual interaction for two sd-shell neutrons coupled to $J^\pi = 0^+$. By ignoring any contributions from the higher lying $d_{3/2}$ orbital, the wave functions may be written as $|0_1^+\rangle = \alpha(1s_{1/2})^2 + \beta(0d_{5/2})^2$ and $|0_2^+\rangle = -\beta(1s_{1/2})^2 + \alpha(0d_{5/2})^2$, where $\alpha^2 + \beta^2 = 1$. The two amplitudes α and β may then be

TABLE I. Experimental and theoretical spectroscopic factors for states in ^{16}C and ^{15}C from the $^{15}C(d,p)^{16}C$ and $^{14}C(d,p)^{15}C$ reactions. The values labeled LSF and WBP correspond to those obtained from Ref. [18] and shell-model calculations with the WBP interaction described in the text, respectively. Experimental uncertainties are in parentheses.

Nucleus	State	$E_{\rm exp}$ (MeV)	$E_{\rm LSF}$ (MeV)	$E_{\rm WBP}$ (MeV)	$S_{\rm exp}$	$S_{\rm LSF}$	$S_{\rm WBP}$
^{16}C	0_1^+	0.000	0.000	0.000	0.60(.13)	1.07	0.60
^{16}C	2_1^+	1.766	2.354	2.385	0.52(.12)	0.63	0.58
^{16}C	0_2^+	3.027	3.448	3.581	1.40(.31)	0.93	1.34
^{16}C	2_2^+	3.986	4.052	4.814	≤ 0.34[a]	0.40	0.33
^{16}C	3_1^+	4.088	···	5.857	0.82–1.06[a]	···	0.92
^{15}C	$1/2^+$	0.000	···	0.000	0.88(.18)[b]	···	0.98
^{15}C	$5/2^+$	0.740	···	0.380	0.69(.14)[b]	···	0.94

[a] Limiting values, assuming that at most 23% of the $2_2^+/3_1^+$ doublet yield can be attributed to the 2_2^+ state.
[b] Experimental values for $^{14}C(d,p)^{15}C$ from Ref. [16].

TABLE II. Residual-interaction matrix elements in MeV for $\nu(sd)^2$ coupled to 0^+ in ^{16}C. Exp, LSF, and WBP are from the present measurement, Ref. [19], and Ref. [26], respectively.

	$(j_1j_2,\, j_1'j_2')$		
$\langle j_1j_2\vert v\vert j_1'j_2'\rangle$	$(\frac{1}{2}\frac{1}{2},\, \frac{1}{2}\frac{1}{2})$	$(\frac{5}{2}\frac{5}{2},\, \frac{5}{2}\frac{5}{2})$	$(\frac{1}{2}\frac{1}{2},\, \frac{5}{2}\frac{5}{2})$
Exp	$-0.92(28)$	$-3.60(28)$	$-1.39(12)$
LSF	-1.54	-2.78	-1.72
WBP	-2.12	-2.82	-1.32

calculated from the measured spectroscopic factors to yield $\alpha = 0.55$ and $\beta = 0.84$. The unperturbed $(1s_{1/2})^2$ and $(0d_{5/2})^2$ energies are calculated from the experimental binding energies of the $1s_{1/2}$ and $0d_{5/2}$ states in ^{15}C measured with respect to the ^{14}C core. The matrix elements $\langle j_1j_2|v|j_1'j_2'\rangle$ are then fixed by the condition that the eigenvalues of the matrix must yield the experimental excitation energies with the measured values of α and β.

Our values for matrix elements of the residual interaction, neglecting any $0d_{3/2}$ contribution, are compared in Table II with the corresponding values derived for the oxygen isotopes in Ref. [19] (LSF), which did include a $0d_{3/2}$ contribution for the 2^+ states as well as core excitation for the 0^+ states, and with those in the current shell-model analysis using the WBP interaction [25], which fit a broader range of data and included the $0d_{3/2}$ orbital but no core excitation. The magnitude of the $(1s_{1/2})^2$ matrix element is smaller, and that of the $(0d_{5/2})^2$ matrix element larger, than those obtained from ^{18}O or from either of the two shell-model interactions. The off-diagonal mixing term is more consistent with the other values.

To show the consistency of the distorted-wave Born approximation analysis, we compare the ratio of the summed $\ell = 2$ and $\ell = 0$ strengths for ^{15}C$(d, p)^{16}$C to the same ratio for ^{14}C$(d, p)^{15}$C. To the extent that the three $\ell = 2$ states in ^{16}C exhaust the $d_{5/2}$ strength and that there are no $d_{3/2}$ contributions, these two ratios should be equal. The resulting ratio is 0.84(.10) for the present data, in agreement with the spectroscopic factors quoted by Goss *et al.* [16] for ^{14}C$(d, p)^{15}$C (see Table I), which give a ratio of 0.78(.15).

The measured spectroscopic factors and deduced wave functions from the present work are consistent with the results of shell-model calculations with a well-accepted interaction and provide a strong basis for comparison to the predictions of other models of the structure of ^{16}C. The same shell-model calculations that correctly predict the neutron-transfer spectroscopic factors also reproduce the most recent observed transition matrix elements in ^{16}C and heavier C isotopes with a consistent set of effective charges [3]. In the context of the current shell-model results, it appears that ^{16}C is not anomalous and can be described without invoking very exotic phenomena.

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