Lifetime Measurement of the First Excited 2^+ State in ^{16}C

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The lifetime of the 2_1^+ state in ^{16}C has been measured with the recoil distance method using the ^{9}Be(^{9}Be, $2p$) fusion-evaporation reaction at a beam energy of 40 MeV. The mean lifetime was measured to be 11.7(20) ps corresponding to a $B(E2;\ 2_1^+ \rightarrow 0^+)$ value of $4.15(73)e^2$ fm^4 [1.73(30) W.u.], consistent with other even-even closed shell nuclei. Our result does not support an interpretation for "decoupled" valence neutrons.

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Nuclei located near the valley of beta stability have strongly correlated proton and neutron spatial distributions. This need not be the case for nuclei with a large excess of one nucleon type, and the search for new phenomena and structure effects due to the "decoupling" of neutrons and protons is of great interest in nuclear structure physics. Examples of such decoupled behavior include neutron halo nuclei [1,2], which have measurably different proton and neutron radial distributions, and low-energy dipole modes such as "pygmy" resonances [3] where, in a simple picture, a core of equal numbers of protons and neutrons oscillates against the excess neutron "skin." Recently another example was suggested to occur in ^{16}C. A lifetime measurement of its first excited state yielded an anomalously small $B(E2; 2_1^+ \rightarrow 0^+)$ value of $0.63e^2$ fm^4 [0.26 Weisskopf units (W.u.)] [4], while inelastic scattering experiments [5,6] indicated a large nuclear deformation ($\beta_2^{pp'} \sim 0.47(5)$ [6]) more typical of neighboring nuclei. The quenched $B(E2)$ value, combined with the large nuclear deformation in ^{16}C, led to the suggestion that its valence neutrons were decoupled from the near-spherical proton core [5–7].

In this Letter we report a model-independent lifetime measurement for the first-excited 2^+ state in ^{16}C. Our data do not support the interpretation of decoupled protons and neutrons in ^{16}C, and are consistent with proton and neutron deformations that follow the systematic trend of other even-even nuclei. The revised value for the ^{16}C $B(E2; 2_1^+ \rightarrow 0^+)$ provides an important benchmark for theory.

The experiment was carried out at the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory. ^{16}C was produced by the ^{9}Be(^{9}Be, $2p$) fusion-evaporation reaction at a beam energy of 40 MeV. The average beam current during the 5 day experiment was ~0.5 pnA. The ^{9}Be target thickness was 1.35(5) mg/cm^2, as determined by energy loss measurements of ^{210}Po α particles through the target. Lifetimes were measured using the recoil distance method [8] in which a 41.5 mg/cm^2 thick, hardened, 99.95% ^{nat}Ta foil was mounted downstream of the Be target. Both Be and Ta foils were mounted on aluminum frames with a 1 cm diameter aperture. The distance between the ^{9}Be target and Ta stopper foil was varied using a set of spacers to give target-stopper distances of 0.64(1), 0.21(1), and 0.08(1) mm. The LIBERACE-STARS detector array, consisting of Compton suppressed HPGe Clover-type detectors [9,10] and large area segmented annular silicon detectors (ΔE-E telescope) [11], was used to detect γ radiation and charged particles. For this experiment two Clover-type γ-ray detectors were placed at 40°, one at 90°, and two at 140° relative to the beam direction at a distance of 16.5 cm from the target. The particle telescope consisted of one 144 μm ΔE and one 1003 μm E detector, separated by 2.5 mm, and mounted 3.0 cm downstream from the target position. A large-area 21 mg/cm^2 thick ^{nat}Ta foil spanned the front of the ΔE detector. The thickness of this foil, combined with the 41.5 mg/cm^2 Ta stopper foil, was sufficient to stop scattered beam and ^{9}Be breakup particles from reaching the ΔE detector.

The experimental trigger required the detection of at least one charged particle in both the ΔE and E detector within a coincidence window of approximately 200 ns. γ-ray events were recorded to disk if they were associated with a valid particle trigger. Offline analysis required the simultaneous detection of two charged particles within a 100 ns coincidence window. A time gate between the two charged particles and the associated γ rays was used to reject uncorrelated events. The silicon detectors were calibrated with an α-emitting ^{226}Ra source. Clover detector energy and efficiency calibrations were determined using ^{56}Co and ^{152}Eu γ-ray sources. The full energy γ-ray detection efficiency was ~1% at 1 MeV, and the 1 proton detection efficiency was ~20%.

The 2-proton ($2p$) fusion-evaporation reaction channel was a key aspect of this lifetime measurement—the large proton binding energy exhausted much of the available

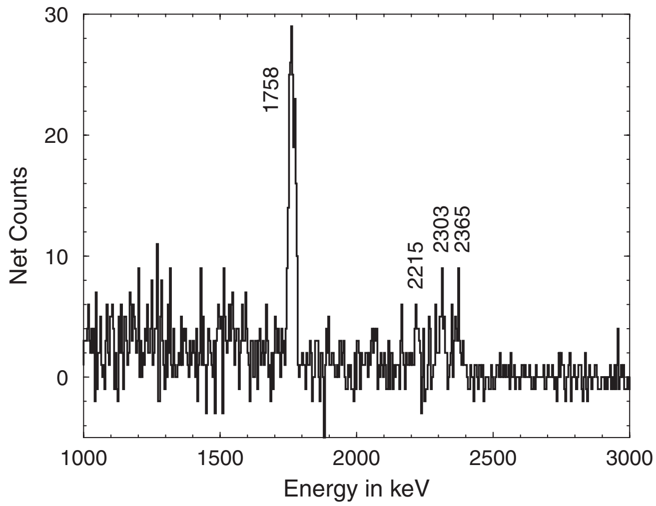

FIG. 1. Spectrum of γ rays in coincidence with 2 protons. Transitions marked by their energies are associated with ^{16}C. Gamma-ray energies were Doppler corrected for a recoil velocity of $v/c = 0.03$. The spectrum shows the combined data from the 0.64 and 0.21 mm distances. The 1758 keV peak contains ~200 counts and corresponds to 36 h beam on target. The dispersion is 4 keV/channel.

excitation energy and significantly suppressed the evaporation of additional neutrons at the chosen beam energy of 40 MeV. The requirement to detect two protons simultaneously in the silicon detectors cleanly selected the weak ~0.3 mb ^{16}C channel from the total ~700 mb cross section estimated for fusion channels (cross sections are taken from PACE [12] statistical model estimates).

Figure 1 shows a portion of the Doppler-corrected spectrum of γ rays in coincidence with two protons. The transition at 1758(2) keV corresponds to the γ decay of the 2_1^+ state in ^{16}C. The three transitions at 2365(4), 2303(4), and 2215(4) keV directly feed the 1758 keV 2_1^+ state and are assigned to the decay of the 4^+, $3^{(+)}$, and 2_2 states, respectively [13–17]. They account for 54(5)% of the total intensity feeding the 1758 keV 2_1^+ state with the remaining intensity coming from unobserved side feeding. The main contaminant peak in the $2p$ gated spectrum is at 741(1) keV from the ^{9}Be(^{9}Be, $2p1n$)^{15}C reaction. The 741 keV state is the only bound state in ^{15}C and does not interfere with the more energetic γ lines in ^{16}C.

Excited-state lifetimes were derived from the observed Doppler-shifted and unshifted components of the γ-ray transition. Gamma-ray spectra for the $2p$ (^{16}C) and $1p1n$

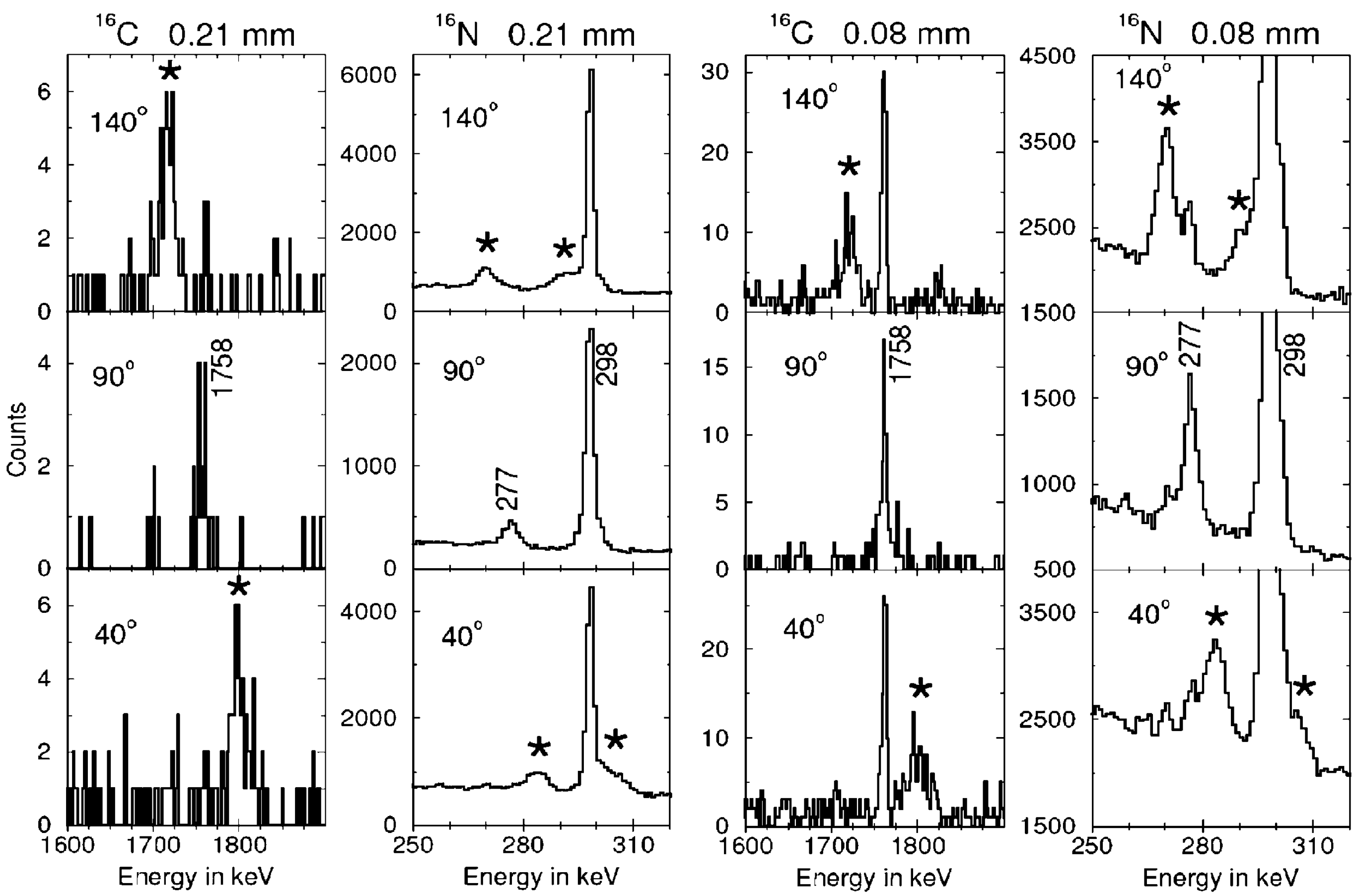

FIG. 2. Gamma-ray spectra for detector angles at 140°, 90°, and 40° obtained at the 0.21 mm (left two columns) and 0.08 mm (right two columns) target-stopper distances for ^{16}C and ^{16}N. 2-proton (^{16}C) gated spectra (first and third columns) and 1-proton, 1-neutron (^{16}N) gated spectra (second and forth columns) are shown. Stars indicate moving peak components.

(^{16}N) reaction channels are shown in Fig. 2 for two of the three target-stopper distances: 0.21 and 0.08 mm. ^{16}N has a 3^- state decaying via a 298 keV γ ray with a mean lifetime of 131.7(19) ps [18], and a 1^- state decaying via a 277 keV γ ray with a mean lifetime of 5.63(5) ps [18]. The ^{16}N γ rays provide an internal calibration for lifetimes extracted in this experiment. The average velocities of the ^{16}C and ^{16}N recoiling nuclei were measured to be $v/c = 0.030(2)$ and $v/c = 0.031(3)$, respectively, from observed Doppler-shifted γ-ray energies. State lifetimes were determined using the relation $N/N_0 = e^{-(t/\tau)}$ where N is the number of counts in the stopped γ-ray peak, N_0 is the sum of moving and stopped peaks, t is the average time taken for the recoil to traverse the gap between the target and stopper foil, and τ is the mean lifetime. The equation is for a single component decay curve. Results extracted from these data, and previously measured values, are summarized in Table I.

At the 0.21 mm target-stopper distance (two left columns of Fig. 2) the ^{16}C 1758 keV γ ray and the ^{16}N 277 keV γ ray show no evidence for a significant (10%) stopped peak component at 40° and 140°. A similar situation is observed for the 0.64 mm distance. Note, if the 2_1^+ ^{16}C lifetime were 77 ps as reported in Ref. [4] we would have observed ~74% stopped component for the 1758 keV transition at this distance. In contrast, the 298 keV γ ray in ^{16}N exhibits both a moving and stopped component. From measurements using the 0.64 mm distance we determine a mean lifetime of 119(14) ps for the ^{16}N 3^- state in agreement with the published value of 131.7(19) ps [18]. At a target-stopper distance of 0.08 mm (two right columns of Fig. 2) the ^{16}C 1758 keV γ ray has both a moving and stopped component. The ratio $[N/N_0 = 46.7(50)\%]$ yields a mean lifetime of 11.7(20) ps for the 2_1^+ state in ^{16}C. The ^{16}N 277 keV transition has $N/N_0 = 21.1(26)\%$ giving a lifetime of 5.6(10) ps in good agreement with the reported value of 5.63(5) ps [18]. The measured lifetime of 11.7(20) ps for the ^{16}C 2_1^+ state corresponds to a $B(E2; 2_1^+ \to 0^+)$ of $4.15(73)e^2$ fm^4 [1.73(30) W.u.], a value comparable to $B(E2)$ values for other closed shell even-even nuclei (for example, Fig. 4 of Ref. [4]).

The lifetime values reported here assume a single exponential decay curve, which is valid for feeding (life)-times far shorter than the state lifetime. The agreement with the ^{16}N adopted values shown in Table I supports this assumption. In ^{16}C the three transitions feeding the 2_1^+ level (Fig. 1) are fully shifted at the 0.08 mm distance implying their mean lifetimes are <4 ps. We note that a 4 ps feeding lifetime (upper limit) would give a reduced ^{16}C 2_1^+ lifetime of ≈ 9 ps, but would not affect the main conclusion of our result.

TABLE I. Transition mean lifetimes obtained in this (τ) and previous (τ prev.) work. The 3^- and 1^- states in ^{16}N provide an internal reference for the ^{16}C value.

Nucleus	Spin	E_γ (keV)	τ (ps)	τ prev. (ps)
^{16}C	2^+	1758	11.7(20) [a]	$77(14)_{\mathrm{stat}}(19)_{\mathrm{syst}}$ [b]
^{16}N	1^-	277	5.6(10) [a]	5.63(5) [c]
^{16}N	3^-	298	119(14) [d]	131.7(19) [c]

[a]From 0.08 mm distance.
[b]Ref. [4].
[c]Ref. [18].
[d]From 0.64 mm distance.

We now discuss the ^{16}C lifetime in relation to neighboring nuclei. ^{16}C consists of 2 proton holes (with the wave function dominated by the $0p_{1/2}^{-2}$ component) and 2 neutrons (mainly $\nu 1s_{1/2}0d_{5/2}$) outside the ^{16}O core (Fig. 3). The ^{18}O 2_1^+ state lies at 1982 keV while the ^{14}C 2_1^+ state is located at 7012(4) keV [17]. The lowest-lying states in ^{16}C are therefore more likely to resemble those of the neutron $\nu(sd)^2$ configuration in ^{18}O. This interpretation is confirmed in earlier (t, p) reaction studies [13–15] and more recently by knockout reactions [19]. Comparing ^{16}C to ^{18}O we find the ^{16}C $B(E2; 2_1^+ \to 0^+)$ of 1.73(30) W.u. to be similar to the ^{18}O value of 3.40(9) W.u. when scaled by Z^2, $(6/8)^2$. This follows from the assumption that the 2_1^+ in both ^{18}O and ^{16}C is a neutron excitation and the $B(E2)$ arises from the effective charge induced by core polarization [20]. Next we consider ^{16}C as ^{14}C + n + n and calculate the value ^{16}C $B(E2; 2_1^+ \to 0^+)$ using the OXBASH shell model code [21] in the modified universal-sd shell [22] model space. The measured ^{16}C $B(E2)$ is reproduced with an effective neutron charge $e_n \approx 0.46$, very close to the standard value $e_n = 0.5$ used in this region. In addition, the mean lifetime of 3.77(10) ns [17] for the $d_{5/2} \to s_{1/2}$ transition in ^{15}C corresponds to $e_n \approx 0.4$ (assuming a pure neutron excitation), which was derived using the expression in Ref. [23] and a value of $\langle d_{5/2}|r^2|s_{1/2}\rangle = 9.07$ fm^2 obtained from harmonic oscillator wave functions.

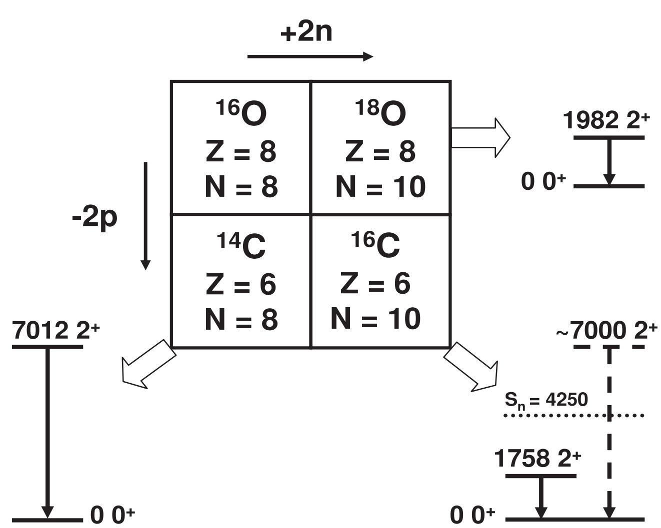

FIG. 3. Schematic comparison of the lowest 2^+ states in ^{18}O, ^{14}C, and ^{16}C. The dashed state and transition at ~7000 keV in ^{16}C is illustrative only and has not been observed experimentally.

The effective charge is a measure of the coupling between valence neutrons and the proton core. The exercise to derive the ^{16}C $B(E2; 2_1^+ \rightarrow 0^+)$ starting from both ^{18}O and ^{14}C establishes the important point that a value for the neutron effective charge ($e_n \approx 0.4$) normal to this region can be applied also to ^{16}C. This means the valence neutrons are coupled to the proton core in ^{16}C with a strength also "normal" to this region.

The ratio of the neutron and proton transition matrix elements, M_n/M_p [24], has also been used to indicate differences between neutron and proton distributions, when compared to the *isoscalar* value $M_n/M_p \sim N/Z$. The relation $\beta_2^{em} = (4\pi/3ZR^2)[B(E2; 0^+ \rightarrow 2_1^+)/e^2]^{1/2}$, with $R = 1.2A^{1/3}$ fm, yields a deformation $\beta_2^{em} = 0.35(6)$ and a "Coulomb" deformation length $\delta_{em} = \beta_2^{em} R = 1.05(18)$ fm for ^{16}C. Combining this value of δ_{em} with the total "nuclear + Coulomb" deformation length taken from inelastic scattering experiments [5,6] we obtain the ratio $M_n/M_p \approx 2.4$ or $M_n/M_p \approx 1.4(N/Z)$, a value close to that of ^{18}O [24,25].

To summarize, the recent suggestion for decoupled neutron and proton matter distributions in ^{16}C has generated much interest. This work reports a model-independent measurement of the lifetime of the ^{16}C 2_1^+ state of 11.7(20) ps, which corresponds to a $B(E2; 2_1^+ \rightarrow 0^+)$ of $4.15(73)e^2$ fm^4 [1.73(30) W.u.], consistent with $B(E2)$ values for other even-even nuclei. This result does not support the interpretation of decoupled valence neutrons. The revised value for the ^{16}C $B(E2; 2_1^+ \rightarrow 0^+)$ provides an important benchmark for theory.

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