Lifetime and $E0$ decay of the first excited 0^+ state in ^{14}C

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The reaction $^2H(^{13}C,p)^{14}C$ has been used to measure the lifetime of the $^{14}C(6.59\ MeV,0^+)$ state. From recoil distance and Doppler shift attenuation measurements a value $\tau = (4.6 \pm 0.7)$ ps was found. The reaction $^{13}C(d,p)^{14}C$ has been used to study the $E0\ \pi$ decay of the 0^+ state. The branching ratio Γ_π/Γ was measured to be $(1.1 \pm 0.1) \times 10^{-2}$. When this value is combined with the determined lifetime an $E0$ matrix element $\langle M \rangle_\pi = (0.36 \pm 0.06)\ fm^2$ is obtained.

[NUCLEAR REACTIONS $d(^{13}C, p)$, E=18.9 MeV; $^{13}C(d, p)$, E=2.7 MeV; ^{14}C measured lifetime and $E0$ branching ratio, deduced $E0$ matrix element. Enriched targets.]

I. INTRODUCTION

This paper reports on a new measurement of the π-branching ratio for the first excited 0^+ state in ^{14}C together with the determination of its lifetime. A previous measurement[1] yielded $\Gamma_\pi/\Gamma = (1.0 \pm 0.4) \times 10^{-2}$. Until recently the lifetime of the state was known only to be $\tau > 0.6$ ps.[2] Both the rather unprecise value of Γ_π/Γ and the upper limit for τ made it worthwhile to undertake experiments to refine the determination of these two quantities.

II. LIFETIME DETERMINATION EXPERIMENTS

A. Recoil distance measurement

A 50 nA ^{13}C beam from the Strasbourg MP tandem was used to bombard at 18.9 MeV a TiD_x target evaporated on a 450 $\mu g/cm^2$ nickel backing. The beam and recoil ions were stopped in the nickel foil of a plunger aligned via optical techniques. The target-to-plunger distances were varied from 38 to 1570 μm. The γ rays were measured in two Ge(Li) detectors. One (114 cm^3) was set at 0° with respect to the beam axis and had a resolution of 2.5 keV for the 1.33-MeV line of a ^{60}Co source. The second (63 cm^3), placed at 125°, had a resolution of 1.7 keV for the 0.34-MeV line of a ^{152}Eu source.

The data were analyzed according to the first-order expression $I_0/(I_0+I_S) = (1-B)\exp(-D/v\tau) + B$, where I_0 and I_S are, respectively, the intensities of γ rays of energy E_0 emitted by nuclei at rest and of γ rays of energy $E_S = E_0(1 + v\cos\theta_\gamma/c)$ emitted at an angle θ_γ by nuclei with velocity v. The length $D = vt$ is the flight path between the target and the stopper, and τ is the mean lifetime of the involved nuclear state. The constant B stands for a background contribution from unidentified target contaminants. In the analysis the average initial velocity of the recoiling ions was calculated from the $E_S - E_0$ energy differences. Corrections for solid angle differences, detection efficiencies, and relativistic effects were made so that the resulting uncertainties are dominated by statistical and systematic errors in extracting the peak intensities.

As a check of our experimental procedure the 726 keV line from the $^{14}N(5.832\ MeV, 3^-) \to {}^{14}N(5.106\ MeV, 2^-)$ γ decay was analyzed from the γ spectra obtained at $\theta_\gamma = 0°$. The analysis was done in two ways: first by fitting the $I_0/(I_0+I_S)$ data [Fig. 1(a)] and second by using an external normalization. The results lead to a mean lifetime $\tau = (12.8 \pm 1.0)$ ps for the $^{14}N(5.382$ MeV) state, taking into account a 5% error on the initial velocity. Corrections for hyperfine perturbations at the recoil velocity are estimated to be negligibly small due to the rather flat angular distribution of the considered γ ray. A Legendre polynomial coefficient of $|a_2| < 0.03$ was measured for this angular distribution. The present lifetime was found to be in good agreement with the value deduced in a recent experiment,[3] namely $\tau = (13.7 \pm 1.1)$ ps.

For the 496 keV $^{14}C(6.590\ MeV, 0^+) \to {}^{14}C(6.094\ MeV, 1^-)$ transition only the data obtained at $\theta_\gamma = 125°$ were analyzed. The overlap with the 511-keV annihilation γ rays did not allow the extraction of the I_S component in the 0° spectra. The data and the fit for the 496-keV line are shown in Fig. 1(a). With symmetrized error bars a value $\tau = (5.0 \pm 1.1)$ ps is adopted from this measurement for the mean lifetime of the $^{14}C(6.589\ MeV, 0^+)$ state.

B. Doppler shift attenuation measurement

In order to confirm the recoil distance measurement (RDM) result for the $^{14}C(6.590$ MeV) lifetime, a Doppler shift attenuation measurement

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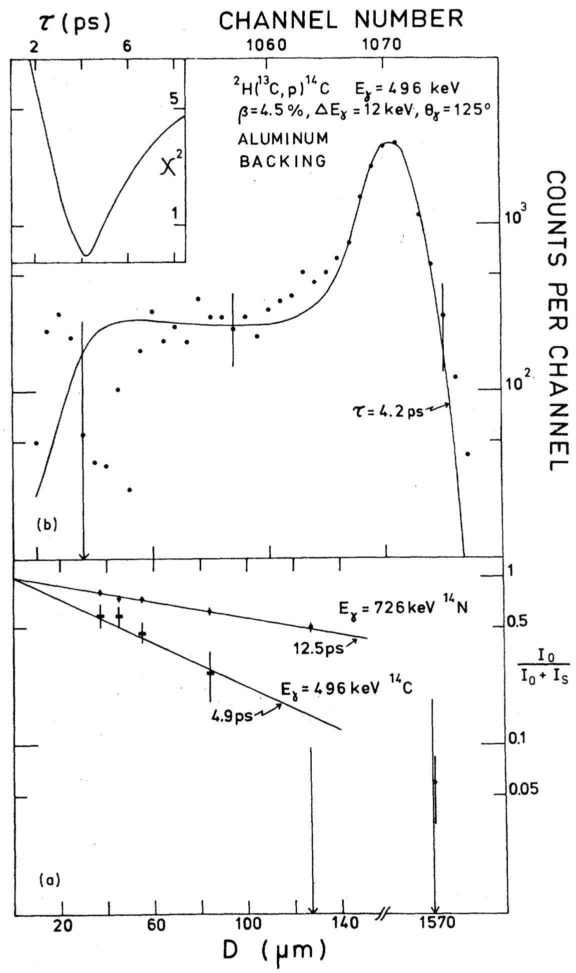

FIG. 1. (a) RDM lifetime results for the ^{14}C (6.590 MeV → 6.094 MeV) and the ^{14}N(5.832 MeV → 5.106 MeV) γ decays. The fits through the data points correspond to the $I_0/(I_0+I_S)$ analysis (see Sec. II. A). (b) Doppler γ-ray pattern for the ^{14}C(6.59 MeV → 6.09 MeV) transition for ^{14}C ions recoiling into aluminum. The energy scale is 0.46 keV/channel. The result of the χ^2 analysis is shown in the insert on the left.

(DSAM) experiment was performed. A 17.6-MeV ^{13}C beam was used to bombard a TiD_x target of ~200 $\mu g/cm^2$ evaporated on a thick aluminum backing. The γ detector was a 10 cm^3 Ge(Li) counter placed at 125° with respect to the beam axis; its energy resolution was 1.9 keV for the 0.34-MeV line of a ^{152}Eu source. In the DSAM analysis the line shape corresponding to the 496-keV transition was computed according to Warburton *et al.*[4] by taking into account the necessary corrections.[4,5] The stopping parameters for ^{13}C recoiling in aluminum were obtained by a least squares fit using experimental data from Ward *et al.*[6] In the notations of Ref. 4, the following coefficients were deduced: $K_n = 0.11$, $K_e = 2.29$, $K_3 = 0.07$, $A = 4.62$, $B = 0.26$, $C = 0.05$, and $v/c = 0.0237$. The estimated uncertainties are 10% on the stopping power. It has been shown in Ref. 7 that for such a scaling of the stopping power, true lifetime values can be deduced from experimental data.

The line shape of the 496 keV γ decay after background subtraction is represented in Fig. 1(b) together with its best fit. The χ^2 fit leads to a lifetime $\tau = (4.2 \pm 1.0)$ ps for the ^{14}C(6.590 MeV) state in agreement with the RDM result.

As a final result for the lifetime of the second 0^+ state in ^{14}C we take $\tau = (4.6 \pm 0.7)$ ps, the averaged value of the two measurements. This value is in agreement with a recent measurement[8] which yielded $\tau = (3.2 \pm 1.1)$ ps.

III. $E0$ π-DECAY MEASUREMENT

The ground state π decay of the 6.59-MeV state was measured by using the experimental technique described in Ref. 9. This technique consists in measuring the light particles feeding the 0^+ excited state through an appropriate nuclear reaction, in singles and in coincidence with the decaying pairs detected in a high efficiency plastic scintillator pair spectrometer. The original design[9] was changed in order to measure electrons up to 7-MeV kinetic energy which was achieved by using full energy 4.5-cm-thick × 8.8-cm-diam Naton 136 scintillators. The other characteristics of the spectrometer, such as detection solid angles, remained the same as in the setup of Ref. 9. The absolute π efficiency of the spectrometer was determined by measuring the almost 100% 6.05 MeV → g.s. π decay in ^{16}O, populated via the $^{19}F(p,\alpha)^{16}O^*$ reaction at $E_p = 1.88$ MeV. From the α-π coincidence spectra and α singles spectra an absolute π efficiency of $(13.8 \pm 0.5)\%$ was deduced for a 570-keV electronic discrimination setting on the electron (positron) spectra. This discriminator setting was also used for the ^{14}C π measurement. A $(14.3 \pm 1.2)\%$ π efficiency for the ^{14}C(6.59 MeV → g.s.) monopole transition was evaluated by following the procedure of Ref. 9.

The $^{13}C(d,p)^{14}C^*$ reaction, at an incident energy of 2.7 MeV, was used to excite the 6.59 MeV 0^+ state. The deuteron beam was delivered by the 7 MV Van de Graaff of Strasbourg onto a 50-$\mu g/cm^2$ carbon self-supporting target 97% enriched in ^{13}C. Protons were detected in a 150 mm^2 × 100 μm-thick surface barrier annular detector at $\bar{\theta}_p = 175°$.

The results of a 6-h measurement with a 20-nA beam current are represented in Figs. 2 and 3. Figure 2(a) shows the singles proton spectrum from the $^{13}C(d,p)^{14}C^*$ reaction. Figure 2(b) is the projection onto the proton energy axis of the two-dimensional proton energy vs π-energy spectrum (not represented) taken simultaneously with the spectrum of Fig. 2(a). Figure 3 displays the projection onto the π-energy axis of the two-dimensional spectrum in proton channels 49–58. The contribution in this spectrum from the 6.59 MeV(0^+) → 6.09 MeV(1^-) → g.s. cascades occurs mainly from the 6.09 MeV → g.s. internal π decay and γ decay (the latter through crystal interactions) because the detection of the 6.59 MeV → 6.09 MeV γ decay is suppressed by the choice of the discriminator settings in the electronics of the full-energy plastic scintillators. Therefore the shape and yield of this contribution in the

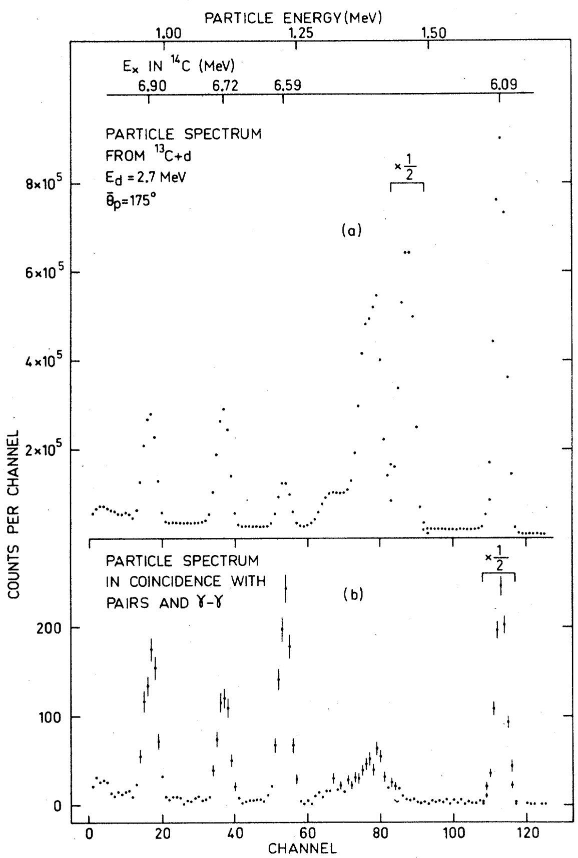

FIG. 2. (a) Direct particle spectrum from $^{13}C + d$ taken simultaneously with the nonrepresented particle energy vs pair energy spectrum. The peak around channel 87 is from deuteron elastic scattering on ^{13}C. The composite peak at channel 78 results from $^{13}C(d,\alpha_2)$, $^{12}C(d,p_1)$, and $^{12}C(d,d)$, ^{12}C being a target contaminant. The background under this peak arises from deuteron scattering in the small target chamber and in the beam stopper. (b) Projection onto the particle energy axis of the two-dimensional spectrum.

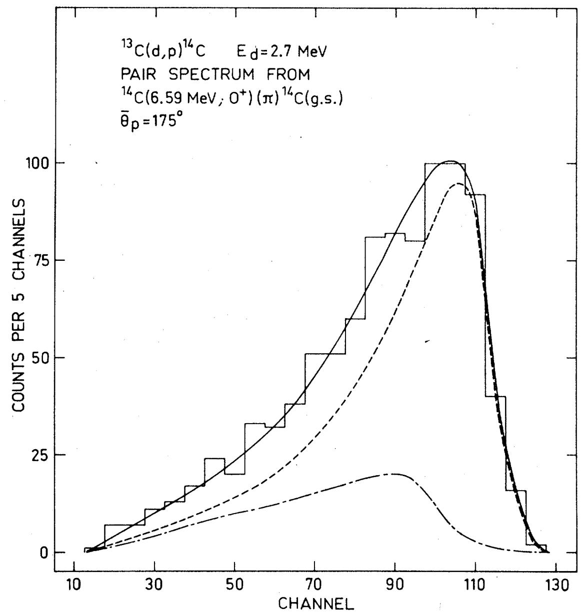

FIG. 3. Pair spectrum obtained from the projection of the events in channels 49–58 of Fig. 2 (b) onto the π-energy axis in the relevant particle energy vs π-energy spectrum. The dashed-dotted line is the yield normalized contribution of the 6.09-MeV decays (see Sec. III) obtained by projecting the events in channels 109–118 of Fig. 2 (b) onto the π-energy axis. The dashed line represents the 6.59 MeV → g.s. π-decay spectrum resulting from the subtraction of this contribution from the yield of the solid curve drawn through the experimental histogram.

spectrum of Fig. 3 (dashed-dotted line) is easily deduced from the coincidence and singles spectra relevant to the 6.09-MeV state which is also populated in the $^{13}C(d,p)^{14}C^*$ reaction (see Fig. 2).

By combining the π yield (dashed line in Fig. 3) with the proton yield in channels 49–58 of Fig. 2(a) and the calculated π efficiency, a value $\Gamma_\pi/\Gamma = (1.1 \pm 0.1) \times 10^{-2}$ is found for the 6.59-MeV state. This result is in good agreement with the value given in Ref. 1. By taking the mean lifetime of the 6.59-MeV state obtained in this work and the above π-branching ratio, the value of the

TABLE I. Properties of the first excited $J^\pi = 0^+$ state in ^{14}C.

E_x (MeV)	τ (ps)	Γ_π/Γ ($\times 10^{-2}$)	$\langle M \rangle_\pi$ (fm^2)	$E0$ strength[a] (s.p.u.)
6.59	4.6 ± 0.7	1.1 ± 0.1	0.36 ± 0.06	0.1

[a] Reference 12.

$E0$ matrix element is found to be $\langle M\rangle_{\pi} = (0.36 \pm 0.06)$ fm^2. The results obtained in the present work are summarized in Table I.

IV. CONCLUSION

As far as the ^{14}C(6.59 MeV→ 6.09 MeV) $E1$ transition is concerned the measured mean lifetime $\tau = (4.7 \pm 0.7)$ ps yields a transition strength of $(3.1 \pm 0.5)\times 10^{-3}$ Weisskopf units (W.u.). This strength is very close to the theoretical prediction of a recent shell model calculation using the modified surface δ interaction,[10] namely $\Gamma/\Gamma_W = 4.3 \times 10^{-3}$ W.u. For the (6.59 MeV→ g.s.) $E0$ decay, the matrix element of (0.36 ± 0.6) fm^2 yields an $E0$ strength of 0.1 single particle units (Table I) which is of the order of those encountered in the middle of the s-d shell for $(4n+2)$ nuclei.[11] Unfortunately, few theoretical calculations have been made for $E0$ decays and a better understanding of the structure of low-lying 0^+ states in the p and s-d shells still awaits a more general description.

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