Lifetimes of the First Excited States of C^{15} and B^{10}†

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The lifetimes of the first excited states of C^{15} and B^{10} have been measured using a pulsed Van de Graaff beam, with a slanted-target technique to reduce the duration of beam pulses on the target. The mean lives of these levels are (3.73 ± 0.23) nsec for C^{15}, and (1.04 ± 0.02) nsec for B^{10}. This result for C^{15}, together with recent gamma angular distribution and stripping measurements, confirms the spin and parity of the first excited state of C^{15} as $\frac{5}{2}+$.

INTRODUCTION

THE available experimental data on lifetimes for γ decay in light nuclei have been reviewed by Wilkinson.[1] This review shows that electric quadrupole transitions are unusual in that the independent-particle shell model (IPM) fails to account for the speed of these transitions, although it describes reasonably well many other properties of light nuclei, including lifetimes for $E1$ and $M1$ transitions. For nuclei with $A\leqslant 20$, $E2$ transitions are faster than the Weisskopf single-particle estimate by a factor of about 5 on the average, and faster than the IPM predictions by a factor of about 30. Such deviations from the predictions of the model in its intermediate-coupling form must presumably be considered to arise from configuration mixing not taken into account in the model.

Alternatively, in the weak-coupling collective model, enhancement of the transition speed over that expected for a single particle outside a spherical core is considered to result from a contribution to the matrix element from surface oscillations of the core. The application of this model to $E2$ transitions in light nuclei has recently been discussed in detail by Raz[2] who finds that the model is quite successful in predicting the *ratios* of transition speeds in many pairs of light nuclei, but fails unaccountably in one case (Ne^{19}).

In this paper, a measurement of the lifetime of the first excited state of C^{15} is reported. The result, together with angular distribution and stripping measurements carried out elsewhere, confirms that the decay of this state is a $d_{\frac{5}{2}}\rightarrow s_{\frac{1}{2}}$ neutron transition outside a C^{14} core. The single-particle model with harmonic oscillator wave functions predicts zero transition probability in this case, and the transition therefore takes place by virtue of refinements to the model, i.e., configuration mixing in shell-model terminology, or surface oscillation effects in the collective model. The C^{15} nucleus is interesting from the collective model point of view in that it has an unusually high value of N/Z for nuclei in this mass region.

A measurement of the lifetime of the $E2$ decay of the $1+$ first excited state of B^{10} to the $3+$ ground state is also reported. This has been measured several times previously, but with one exception these measurements have employed either recoil techniques or observation of the centroid shift of the time spectrum of the delayed radiation compared with that of a prompt gamma. In the present work the exponential decay of the level was observed directly. A lifetime measured in this way is insensitive to many systematic errors associated with centroid shift measurements.

EXPERIMENTAL PROCEDURE

Beam Pulsing System and Slanted-Target Time-Compression Technique

The lifetime measurements reported in this paper were made using the pulsed beam of the Brookhaven National Laboratory Van de Graaff accelerator. A slanted-target time-compression technique was employed. This technique is described briefly below; a more detailed description of the system and an analysis of its operation will be published elsewhere.[3]

The principle of the slanted-target time-compression technique, which is a development of a time-compression system suggested independently by Devons[4] and Shapiro,[5] is shown in Fig. 1. Figure 1(a) shows the profile of the beam at a given instant in time as it emerges from the rf deflection plates. Figure 1(b) illustrates the effect of a focusing lens on the unswept beam, and in Fig. 1(c) the combined effect of beam sweeping and focusing are shown together with the position of the slanted target. Figure 2 presents experimental data to illustrate the effect of target angle on time resolution. It is clear that an appropriate choice of target angle can reduce substantially the duration of the beam pulse on the target.

In the present system, the beam passes through

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* Present address: Bell Telephone Laboratories, Murray Hill, New Jersey.
[1] D. H. Wilkinson, *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Chap. VF.
[2] B. J. Raz, Phys. Rev. **120**, 169 (1960).
[3] J. V. Kane, M. A. El-Wahab, J. Lowe, and C. L. McClelland, Proceedings of the International Conference on Nuclear Electronics, Belgrade, May 1961 (to be published), and Bull. Am. Phys. Soc. **6**, 253 (1961).
[4] S. Devons, *Proceedings of the Rehovoth Conference on Nuclear Structure* (North-Holland Publishing Company, Amsterdam, 1958), p. 547.
[5] F. L. Shapiro, Instr. Exptl. Tech. (U.S.S.R.) **1**, 33 (1957).

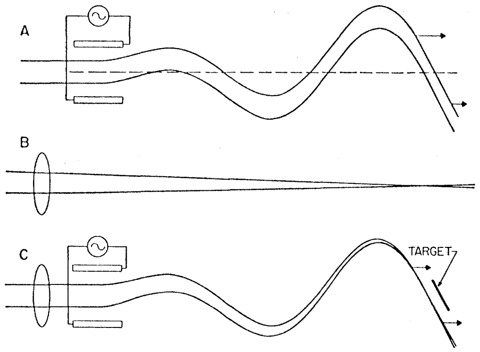

FIG. 1. Principle of the slanted-target technique as a time-compression method.

electrostatic focusing quadrupoles and then between two sweeping plates, 30 cm long, spaced 1 cm apart. A rf voltage, 20 kv peak to peak, at 7.6 Mc/sec, is supplied to these plates, sweeping the beam vertically. The slanted target is located about 2.5 m from the sweeping plates. It can be shown[3] that the duration of the beam pulse on the target depends essentially on the height of the focused beam spot at the target position, and on the ratio of the amplitude of the swept beam to its wavelength. From measurements of the unswept focused-beam spot on quartz, it is estimated[3] that the duration of the beam pulse on the target is 0.8×10^{-10} sec. Average beam currents of 1×10^{-8}–5×10^{-8} amp are readily available.

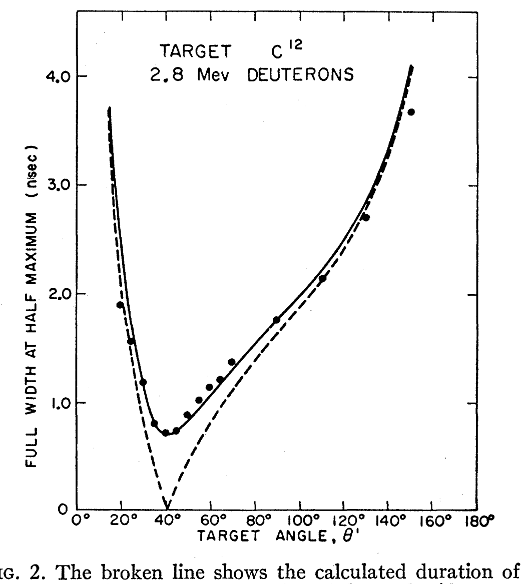

FIG. 2. The broken line shows the calculated duration of the beam pulse on the target as a function of the angle θ' between the target and the direction of the unswept beam. A beam of infinitely thin cross section is assumed. If the electronics and finite beam thickness are assumed to contribute a constant width of 0.7 nsec to the over-all time resolution, the full line shows the predicted variation of the full width at half maximum of the time distribution as a function of θ'. The experimental points were obtained using gammas from the reaction $C^{12}(d,p)C^{13*}$, with the gamma detector channeled at 800 kev.

ELECTRONIC EQUIPMENT

A block diagram of the electronic equipment is shown in Fig. 3. Radiation from the target is detected by a scintillation counter using a RCA type C7260B photomultiplier. Fast signals from the anode are fed through a 404A pentode limiter and two distributed amplifiers to a time to pulse-height converter of the rf vernier type.[6] Linear signals from dynode 7 are fed to a single-channel analyzer and are used to gate the 400-channel analyzer displaying the output of the time to pulse-height converter. Throughout the present experiments, an auxiliary circuit was used to block the analyzer gate for 50 μsec after each pulse in the counter (whether in the channel or not). This was found to produce a noticeable improvement in time resolution even at counting rates of only a few thousand per sec.

Using a 1 in.$\times1\frac{1}{4}$ in. Pilot-B scintillator, a time resolution (full width at half-maximum) of 0.4 nsec has been observed for 3-Mev gammas from the reaction $C^{12}(d,p\gamma)C^{13}$. The sides of the peak had exponential slopes which decreased by a factor of 2 in 0.7×10^{-10} sec. This width is consistent with values previously observed for this type of photomultiplier.[7] It arises mainly from the finite time resolution of the photomultiplier, although energy instability and inhomogeneity in the Van de Graaff beam also contribute to the time resolution observed in these experiments. The performance was worse at lower gamma energies: at 850 kev, widths of 0.7 nsec and slopes of 0.1 nsec for a factor of 2 are typical for runs of several hours duration.

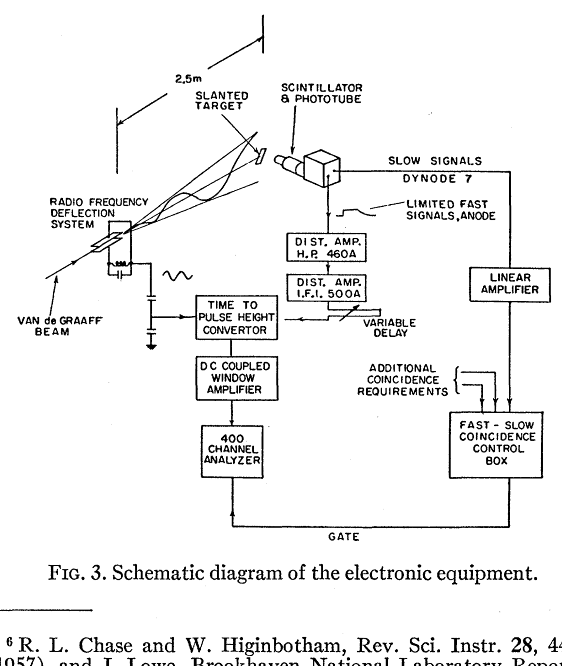

FIG. 3. Schematic diagram of the electronic equipment.

[6] R. L. Chase and W. Higinbotham, Rev. Sci. Instr. 28, 448 (1957), and J. Lowe, Brookhaven National Laboratory Report, BNL 6140 (unpublished).

[7] J. V. Kane, R. E. Pixley, R. B. Schwartz, and A. Schwarzschild, Phys. Rev. 120, 162 (1960).

THE B^{10} EXPERIMENT

The 717 kev first excited state[8] of B^{10} can conveniently be produced either by the $Be^9(d,n)B^{10*}$ or $B^{10}(p,p')B^{10*}$ reactions. Both were used during the present experiment. For the $Be^9(d,n)B^{10*}$ runs, the target, a 0.0025-in. Be foil, was bombarded with 2.7-Mev deuterons. A $1\frac{3}{4}$-×2-in. Pilot-B scintillator was mounted on the C7260B photomultiplier. A scintillator of this size did not yield such good time resolution as the 1 in.×$1\frac{1}{4}$ in. used during testing, but the observed full width at half-maximum of 1.1 nsec was adequate for the lifetime studied here.

The detector was situated 110 cm from the target, at 90° to the beam direction. It was surrounded by a neutron-gamma shield consisting of a $2\frac{1}{2}$-in. thickness of lead, an 8-in. thickness of a paraffin-LiF mixture, and at least 12 in. of paraffin on all sides of the detector.[9] The outer paraffin layer was increased to about 30 in. on the side facing the Van de Graaff.

The target to detector distance was chosen so that the flight time of the highest energy neutron group from the target was long enough to permit the observation of the exponential decay of gammas through 10 half-lives, followed by about 20 nsec of background, free of neutron groups.

The spectrum in the plastic scintillator is shown in Fig. 4. The single-channel analyzer was channeled as shown on the 717-kev gamma. For a comparison source of prompt gammas, the reaction $C^{12}(d,p\gamma)C^{13}$ was employed with the channel set at 717 kev as before. To minimize errors due to a gradual drift of the centroid position, the carbon and beryllium targets were bombarded alternately; 30 five-min runs were taken on each target.

For the $B^{10}(p,p')B^{10*}$ runs a thick natural-boron target was bombarded with 2.7-Mev protons. Since the neutron yield from the target was negligible, the shield described above was not used. Prompt comparison runs were taken by frequent alternation of the boron target with an aluminum target, using the same gamma channel in both cases.

THE C^{15} EXPERIMENT

The first excited state[8,10] of C^{15} at 750 kev was produced in the reaction $C^{14}(d,p)C^{15*}$. The target[11] was elemental carbon enriched to 80% C^{14} which had been deposited on a silver foil by passing an electrical discharge through acetylene gas prepared from $BaCO_3$ enriched in C^{14}. The thickness of carbon was about 1 mg/cm^2.

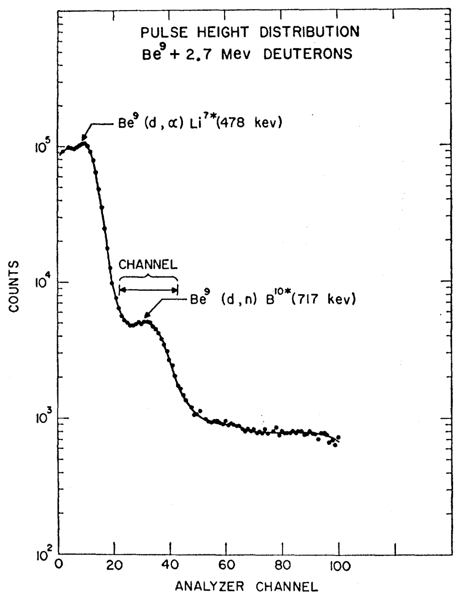

FIG. 4. Pulse-height distribution in the plastic scintillator from the deuteron bombardment of Be. The single channel discriminator was channeled as shown on the 717-kev gamma from $Be^9(d,n)B^{10*}$.

At the maximum energy available on the Brookhaven National Laboratory Van de Graaff, the yield from this reaction is still quite low, and the following steps were taken to achieve as high as possible a ratio of 750-kev gamma yield to neutron and gamma background:

(i) A 2-×2-in. NaI (Tl) scintillator was used on the C7260B photomultiplier to reduce the relative contribution from the Compton distributions of higher energy gammas. The time resolution observed with this scintillator was about 2.5 nsec.

(ii) The neutron and gamma shield described above was used.

(iii) To reduce the background from beam swept onto the beam pipe, collimator slits and the rf sweeping plates, the beam was also pulsed in the terminal of the Van de Graaff before acceleration, using a terminal pulsing system previously installed by Turner and Bloom.[12] This system produces pulses about 5 nsec wide, separated by about 130 nsec. A rf signal radiated by an electrode on the side of the terminal is picked up by another electrode in the Van de Graaff tank. This rf signal was amplified and used to drive the external rf beam pulsing unit, enabling the terminal pulser to be synchronized with the external pulsing system. This system has the additional advantage that for a given beam on target the average beam current in the accelerator tube of the Van de Graaff is substantially reduced, permitting the machine to run at high energies with better stability.

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[8] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[9] The inner shield has been described by H. H. Landon, A. J. Elwyn, G. N. Glasoe, and S. Oleska, Phys. Rev. **112**, 1192 (1958).
[10] L. F. Chase and E. K. Warburton, Lockheed Aircraft Corporation Report LMSD-703105 (unpublished), and L. F. Chase, R. G. Johnson, F. J. Vaughn, and E. K. Warburton, Phys. Rev. (to be published).
[11] The C^{14} target was kindly supplied by Dr. J. N. McGruer, Pittsburgh University.
[12] C. M. Turner and S. D. Bloom, Rev. Sci. Instr. **29**, 480 (1958).

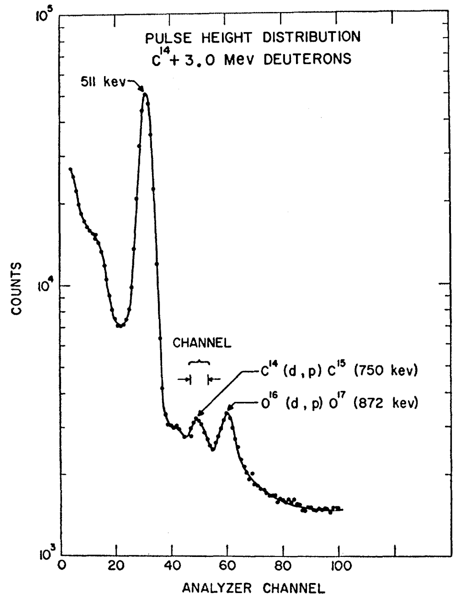

FIG. 5. Pulse height distribution in the NaI scintillator from the bombardment of C^{14} with 3-Mev deuterons. The single channel discriminator was channeled on the 750-kev gamma photopeak as shown.

The spectrum in the NaI(Tl) scintillator is shown in Fig. 5. It can be seen that, in spite of the precautions outlined above, the yield of the 750-kev gammas remains small compared with the neutron and gamma background. The response of the detector to slow neutrons could have been reduced by using a plastic scintillator, but it was found that, provided a sufficiently narrow channel on the photopeak (as shown in Fig. 5) was used, a better ratio of 750-kev gamma yield to neutron background effects could be obtained with NaI(Tl).

In view of the high background in the experimental channel as shown in Fig. 5 it is essential to verify that any observed exponential decay is in fact due to the 750-kev gamma. To achieve this, a 64×64 channel two-dimensional analyzer[13] was used, in addition to the electronics described above, to display pulses from the time to pulse-height converter on one axis, and the gamma pulse-height spectrum from the linear amplifier on the other axis. As discussed below, data from the two-dimensional analyzer enable the source of the observed exponential decay to be established unambiguously.

Three runs, totaling about 40 hr of machine time, were taken at a deuteron energy of 3.0 Mev. As in the $Be^9(d,n)B^{10*}$ experiment, a carbon target was used to provide prompt comparison data.

THE TIME CALIBRATIONS

The experimental runs were interspersed with frequent calibrations of the time to pulse-height converter. These were carried out by inserting known lengths of RG63/U cable into the fast signal lead. The signal velocity in RG63/U cable was determined in the following way.

A measurement of the frequency of the sweeping rf gave an accurate value for the time between consecutive beam pulses at corresponding positions on the rf cycle. A length of RG63/U cable with a delay approximately equal to the time between such beam pulses (~133 nsec) was inserted in the fast signal lead; the output of the time to pulse-height converter shifted only slightly, this shift representing the difference between the delay of the cable and the time between beam pulses. A calibration of the time to pulse-height converter with lengths of the same cable then permitted calculation of the exact cable length with a delay corresponding to one rf cycle. From these data the signal velocity in the RG63/U cable could be calculated. An advantage of this method is that the velocity is measured for the actual pulse shape used during the experiment, so that errors do not arise from dispersion in the cable.

Systematic errors in this measurement arise from the attenuation of the pulse in the cable and from degradation of its rise time. The effect of attenuation can be measured directly; that of degradation of rise time can only be estimated, but the combined error due to these effects is estimated to be less than 0.2%. In any case, these effects are partially compensated since both effects are present when the cable is used for time calibration purposes.

The signal velocity found, (0.817 ± 0.003) c, has been confirmed in independent measurements[14] on a sample from the same roll of RG63/U by direct comparison with an air dielectric delay line.

Some nonlinearity of the time to pulse-height converter was observed. Calibration of the converter was therefore carried out over a wide range of delays (~35 nsec), over which the nonlinearity was generally about 3%. This enabled a better measurement to be made of the mean slope in the narrower range involved in the experiment. Nevertheless, it is estimated that an uncertainty of about 2% remains in the time calibration from this source.

As an absolute check on the time calibration procedure, the flight time of gammas over a known distance was measured by observing the shift of the centroid of the time spectrum of prompt gammas as the target-to-detector distance was varied. Also, the flight time of the ground state neutron group from $C^{12}(d,n)N^{13}$ was determined by measuring the time separation of this neutron group and the prompt gammas from $C^{12}(d,p\gamma)C^{13}$ as a function of target-to-detector distance. Both these measurements confirmed the time calibra-

[13] R. L. Chase, Brookhaven National Laboratory Report BNL 3838 (unpublished).

[14] These measurements were carried out by A. Schwarzschild and A. C. Li of this laboratory, who have observed 5% variation in signal velocity between different samples of RG63/U.

tion technique within their errors, which were estimated to be 8% and 3%, respectively.

RESULTS

Boron

The data from the $Be^9(d,n)B^{10*}$ runs are shown in Fig. 6. Background has been subtracted, and the outer pair of arrows mark the region over which the lifetime was determined. The line shown is a least-squares fit to the points. The fit corresponds to a mean life of (1.04 ±0.023) nsec; a value within 0.5% of this results from using the narrower region, defined by the inner pair of arrows, for the fit. The error quoted above includes errors in the time calibration and in the determination of signal velocity in the calibration cable.

The centroid shift between the time spectra for the delayed radiation and the prompt comparison in Fig. 6 is 0.75 nsec. For pure radiations this shift should equal the mean life of the delayed gamma.[15] The observed value therefore reflects the presence of about 28% of a prompt component in the total spectrum, a value entirely consistent with the energy spectrum of Fig. 4. The analysis technique of Birk *et al.*[16] can be used to extract the mean life in such a case, and for the present data this analysis yields $\tau_m = 1.02$ nsec, a value in close agreement with that obtained from the exponential decay.

The data from the $B^{10}(p,p')B^{10*}$ runs are shown in Fig. 7. As can be seen from the figure, two exponential

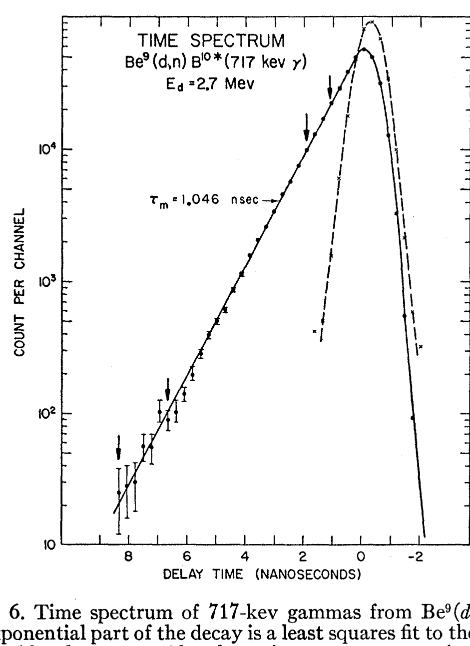

FIG. 6. Time spectrum of 717-kev gammas from $Be^9(d,n)B^{10*}$. The exponential part of the decay is a least squares fit to the region indicated by the arrows. Also shown is a prompt comparison curve obtained using gammas from the $C^{12}(d,p)C^{13*}$ reaction.

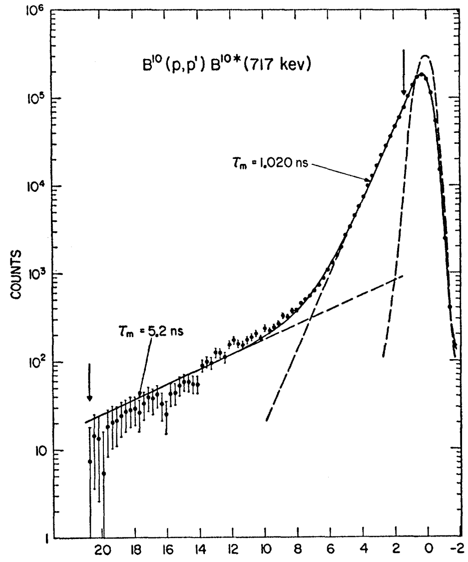

FIG. 7. Time spectrum of 717-kev gammas from the proton bombardment of boron. The faster component is attributed to the $B^{10}(p,p')B^{10*}$ (717-kev) reaction. The full curve is a least-squares fit to the sum of two exponential decays in the region indicated by the arrows. Also shown is a prompt comparison curve obtained using gammas from the $Al^{27}(p,p')Al^{27*}$ reaction.

decays are present in the data. The data were analyzed by means of a computer program[17] which carries out a least-squares fit to the sum of two exponential decays, varying simultaneously both the slopes and intercepts of the two components. The results of this analysis are shown in Fig. 7. The shorter of the two lifetimes is attributed to the decay of the first excited state of B^{10}, and the mean life obtained is (1.020±0.029) nsec, where the error quoted again includes errors in the time calibration and an additional error of 2% arising from systematic uncertainties in the two-component analysis of the data. This value is in agreement with that obtained from the $Be^9(d,n)B^{10*}$ runs, and the weighted mean from the two sets of runs is

$$\tau_m = (1.04 \pm 0.02) \text{ nsec.}$$

The lifetime of the longer component observed in the $B^{10}(p,p')B^{10*}$ runs is not well determined by the data, largely because of the poorer statistics in this region. The value obtained from the two-component least squares analysis is

$$\tau_m = (5.2 \pm 1.5) \text{ nsec.}$$

The source of the radiation with this lifetime has not yet been established.

Carbon

The time spectrum obtained from the $C^{14}(d,p)C^{15*}$ runs at a deuteron energy of 3 Mev is shown in Fig.

[15] T. D. Newton, Phys. Rev. **78**, 490 (1950).
[16] M. Birk, G. Goldring, and Y. Wolfson, Phys. Rev. **116**, 730 (1959).

[17] The authors are grateful to Dr. A. Poskanzer and Dr. J. B. Cummings for the use of their IBM 704 program for the analysis of decay curves containing more than one component.

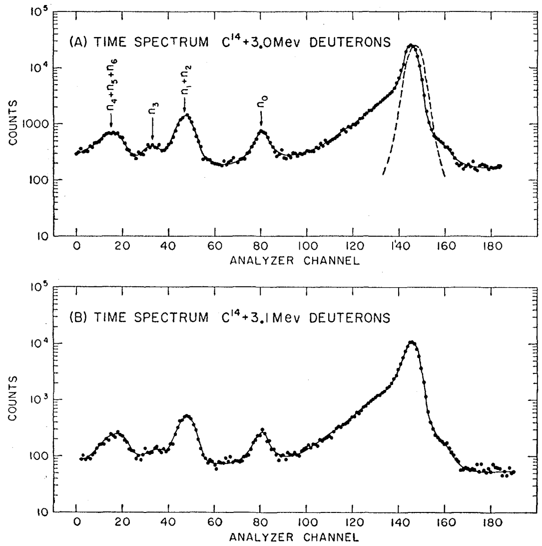

FIG. 8. Time spectrum of pulses from the deuteron bombardment of C^{14}, (a) at 3.0 Mev and (b) at 3.1 Mev. The groups labeled n_0 to n_6 are attributed to neutrons from the reaction $C^{14}(d,n)N^{15}$ leaving N^{15} in excited states as follows: n_0, ground state; n_1 and n_2, 5.28 and 5.30 Mev (not resolved); n_3, 6.33 Mev; n_4, n_5, and n_6, 7.16, 7.31, and 7.57 Mev (not resolved). The bump on the prompt side of the prompt peak is electronic in origin, and does not affect the region of the exponential decay.

8(a). Immediately following the prompt peak is a region of exponential decay, which is attributed (see below) to the decay of the first excited state of C^{15}. The peaks labeled n_0 to n_6 on the figure are attributed to neutrons from the reaction $C^{14}(d,n)N^{15}$, leading to the states in N^{15} indicated in the caption. The flight time of the ground state neutron group can be calculated from the known Q value for the reaction to about 1%, the error resulting mainly from uncertainty in the target thickness. The time separation of this group from the prompt gamma peak in Fig. 8 therefore provides an internal check on the time calibration. The calculated flight time agrees with the value deduced from the data of Fig. 8 to within 2%.

The ground state neutron group corresponds to a neutron energy of approximately 10 Mev. Since neither C^{12} nor any known target contaminant produce neutrons of appreciably higher energy, the region of exponential decay was assumed not to be distorted by weak, high-energy neutron groups. However, neutrons of 0.3–0.4 Mev, from the preceding beam pulse, may lie in the region of the exponential decay. As a test of this possibility, a run was made at an incident deuteron energy of 3.1 Mev, and is shown in Fig. 8(b). The deuteron energy shift of 100 kev would shift a neutron group from the preceding pulse by ~50 channels. Since there is no apparent difference between the runs at 3.0 and 3.1 Mev, it was assumed that the exponential decay is not appreciably distorted by low-energy neutron groups.

The principal difficulty in extracting the lifetime from the data is the uncertainty in the background to be subtracted. Therefore, trial values for the background were subtracted and a final value was chosen for which the region immediately following the prompt peak was closest to a pure exponential. This criterion was applied both by a visual examination of the straightness of the line, and, more quantitatively, by the requirement of lowest external error on a least-squares fit of an exponential decay to the data. As an indication of the accuracy of this method, a trial value of the background for which the external error was 20% higher than the lowest obtained (and which left a clearly visible curvature in the data) yielded a value for the lifetime 5% different from that obtained using the best value for the background.

The data from 40 hrs bombardment at 3.0 Mev after background subtraction are shown in Fig. 9, together with a least-squares fit to the points between the outer pair of arrows. The corresponding mean life is 3.73 nsec and the region of data between the inner pair of arrows yields a value within 0.2% of this. The main source of error arises from the difficulty in determining the background which as discussed above, leads to an uncertainty of 5%. An additional uncertainty of 3% arises from the time calibration, giving a final result of

$$\tau_m = (3.73 \pm 0.23)\ \text{nsec}.$$

The data from the two-dimensional pulse-height analyzer enable the gamma-energy spectrum to be examined at any time delayed relative to the prompt peak. A set of four spectra for delays between 5.1 and 11.6 nsec are shown in Fig. 10(a). These spectra essentially differ only in the intensity of the 750-kev photopeak. In Fig. 10(b) the integrated area under the 750-

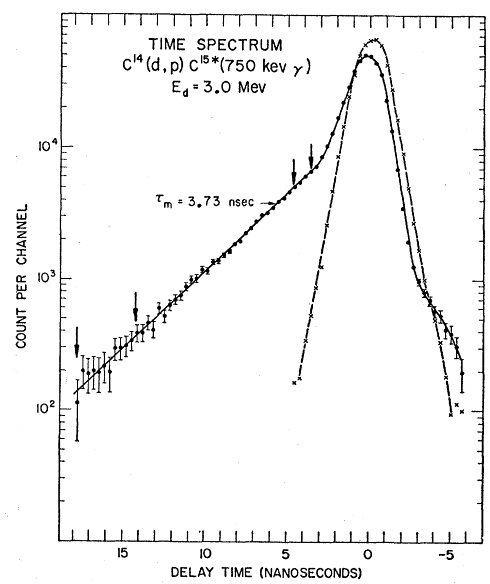

FIG. 9. Time spectrum of 750-kev gammas from $C^{14}(d,p)C^{15*}$. The exponential part of the decay is a least squares fit to the region of the data indicated by the arrows. Also shown is a prompt comparison curve using gammas from the $C^{12}(d,p)C^{13*}$ reaction.

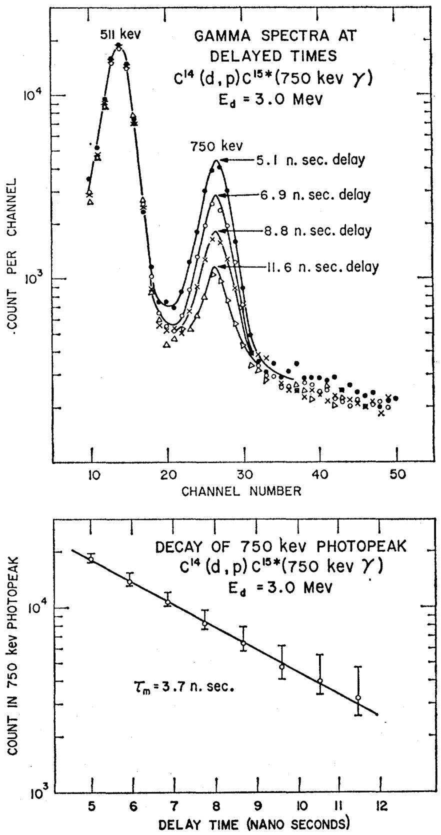

FIG. 10. (a) Gamma pulse height spectra from the deuteron bombardment of C^{14}. The data were recorded by the two-dimensional analyzer and correspond to delays of 5.1, 6.9, 8.8, and 11.6 nsec respectively, relative to the prompt peak. (b) Time spectrum of 750-kev gammas from $C^{14}(d,p)C^{15*}$. The points represent the integrated area in the 750-kev gamma photopeak curves shown in (a). The indicated errors include the uncertainty in the graphical subtraction of the background in these curves.

kev photopeak is plotted as a function of delay. The lifetime obtained from this curve, $\tau_m=(3.7_{-0.5}^{+1.0})$ nsec, is not as accurate as that from the data of Fig. 9, largely due to uncertainties in background subtraction in the curves of Fig. 10(a). However, the agreement with the more accurate result confirms unambiguously that the exponential decay observed in Fig. 9 is due to a 750-kev gamma.

DISCUSSION

B^{10}

The present result for B^{10} is in agreement with many of the earlier measurements[16,18,19] using recoil or centroid shift techniques, although somewhat higher than the weighted mean of these measurements, $\bar{\tau}_m=0.95\pm0.04$ nsec. The value reported here does not agree with the recent exponential decay measurement of Gorodetzky *et al.*[20] who found $\tau_m=(0.895\pm0.044)$ nsec.[20a]

Theoretical calculations of the IPM prediction for this lifetime have been published by Kurath[21] and by French and Fujii.[22] The prediction is sensitive to the value chosen for the intermediate-coupling parameter, a/K. At $a/K=4.75$, which gives the best agreement with experiment for the predicted level positions,[23] the theoretical mean life[24] is approximately 4 nsec. However, the predicted transition rate is faster in the region $a/K=4.0$, and the present result is in agreement with the theory at $a/K\simeq3.8$. At a value of a/K of 4, the agreement with experiment of the level energies is still reasonably good, particularly if L/K is reduced[23] from 6.8 to 5.8. Thus, it may still be possible to account for the experimental lifetime without invoking the collective enhancement mentioned by Bloom *et al.*[25] A more precise determination of the value of a/K from other data would be required to decide this point.

C^{15}

The present result confirms[10] the $\frac{5}{2}+$ assignment for the 750-kev level in C^{15}. If the spin were $\frac{7}{2}$, the observed transition rate would correspond to 3×10^5 and 10^7 times the Weisskopf estimate, for odd and even parity respectively. These values clearly violate sum rules[1] and higher spin assignments do so even more strongly. In a measurement of the gamma angular distribution in the $C^{14}(d,p\gamma)C^{15}$ reaction, Chase *et al.*[10] observed a $\cos^4\theta$ term. Thus the spin cannot be less than $\frac{5}{2}$. From these data and the present result, it is concluded that the spin is $\frac{5}{2}$. If the parity were odd, the $M2$ transition rate would correspond to 10 times the Weisskopf estimate. This is extremely unlikely,[1] though it cannot be ruled out rigorously. Further evidence for the $\frac{5}{2}+$ assignment comes from angular distribution measurements[26] for the $C^{14}(d,p)C^{15}$ reaction, which indicate that the neutron reduced width[27] is about four times the single-particle width for an $l=3$ transition, but is approximately equal

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[18] For example, R. E. Holland, F. J. Lynch, and S. S. Hanna, Phys. Rev. **112**, 903 (1958) who give references to earlier work.

[19] S. Gorodetzky and A. Knipper, J. phys. radium **19**, 83 (1958).

[20] S. Gorodetzky, R. Richert, R. Manquenouille, and A. Knipper Nuclear Phys. **17**, 684 (1960).

[20a] *Note added in proof.* More recent measurements by Gorodetzky *et al.*, yielded $\tau_m=(1.04\pm0.03)$ nsec, in agreement with our result (A. C. Knipper, private communication).

[21] D. Kurath, Phys. Rev. **106**, 975 (1957).

[22] J. B. French and A. Fujii, Phys. Rev. **105**, 652 (1957).

[23] D. Kurath, Phys. Rev. **101**, 216 (1956).

[24] The authors are grateful to Professor D. H. Wilkinson for pointing out that the predictions of references 21 and 22 can be improved by using, instead of an approximate value for the rms radius, a value derived from the experimental electron scattering results [R. Hofstadter, H. R. Fechter, and J. A. McIntyre, Phys. Rev. **92**, 978 (1953), and H. F. Ehrenberg, R. Hofstader, U. Meyer-Berkhout, D. G. Ravenhall, and S. E. Sobottka, *ibid.* **113**, 666 (1959)]. The predictions quoted here are accordingly based on a rms radius of 2.5×10^{-13} cm.

[25] S. D. Bloom, C. M. Turner, and D. H. Wilkinson, Phys. Rev. **105**, 232 (1957).

[26] W. E. Moore, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

[27] We use the prescription of M. H. MacFarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960), for the extraction of reduced widths from stripping data, and we take their results for the single particle reduced widths.

to the $l=2$ reduced width. Thus the $\frac{5}{2}-$ assignment is excluded, and the level is established definitely as $\frac{5}{2}+$.

The transition involved is presumably, therefore, a $d_{\frac{5}{2}}\rightarrow s_{\frac{1}{2}}$ neutron transition outside a C^{14} core.[28] The observed transition speed is about 0.4 times the Weisskopf estimate for a single proton. This implies configuration mixing in the wave function of the odd neutron, and the participation of parent states in C^{14} having a substantial $E2$ radiative width to the C^{14} ground state. Two 2+ states in C^{14} are predicted[29] at excitations of 7.01 and 8.32 Mev, but too little is known about their radiative widths to enable quantitative estimates to be made of their effect on the C^{15} lifetime.

On the weak-coupling collective model, the transition is considered to take place through oscillations of the nuclear surface induced by the odd neutron. Thus the present result for C^{15} should be directly related to lifetimes for other $d_{\frac{5}{2}}\leftrightarrow s_{\frac{1}{2}}$, single neutron transitions, provided the surface deformability is the same in each nucleus considered. The model has been examined in detail for nuclei in this mass region by Raz.[2] Taking the value for the surface deformability parameter C deduced by Raz for the $s_{\frac{1}{2}}\rightarrow d_{\frac{5}{2}}$ neutron transition in O^{17}, the C^{15} lifetime is predicted[30] to be (5.20 ± 0.37) nsec. A reasonable explanation for this discrepancy is that the parameter C is lower for the C^{14} core in C^{15} than for the O^{16} core in O^{17} by a factor 0.85. This corresponds to a more easily deformable core, and a change in this direction is expected when moving away from a closed shell.

SUMMARY OF RESULTS

The results of the present experiments are summarized here. The lifetime for the $\frac{5}{2}+\rightarrow\frac{1}{2}+$ transition in C^{15} was found to be

$$\tau_m=(3.73\pm0.23)\text{ nsec},$$

and for the $1+\rightarrow3+$ transition in B^{10},

$$\tau_m=(1.04\pm0.02)\text{ nsec}.$$

Alternatively, as suggested by Wilkinson,[1] these may be expressed in terms of the Weisskopf units with

$$r_0=1.2\times10^{-13}\text{ cm}:$$

For C^{15},

$$\Gamma_\gamma=(0.431\pm0.026)\Gamma_W;$$

and for B^{10},

$$\Gamma_\gamma=(3.17\pm0.07)\Gamma_W.$$

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[28] C.f. E. C. Halbert, Ph.D. thesis, University of Rochester, 1956 (unpublished).

[29] E. K. Warburton and W. T. Pinkston, Phys. Rev. **118**, 733 (1960).

[30] In reference 2, the value of the matrix element of the surface coupling term, $\langle 2s|k|1d\rangle$, was assumed to be constant for nuclei in this mass region. In the present analysis, values of this matrix element computed by G. R. Satchler (private communication through B. J. Raz) were used. The computed values deviate from constancy by about 20% over the three nuclei considered here.

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Positron Emission in the Decay of K^{40}†

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Positron emission has been detected in the decay of K^{40} in a triple coincidence experiment using a liquid-scintillation positron detector and two NaI(Tl) annihilation gamma detectors. A ratio of $\beta^+/\beta^-=(1.12\pm0.14)\times10^{-5}$ was found. This corresponds to a ratio of the squared matrix elements of $M_+^2/M_-^2=0.18\pm0.03$ which is in substantial agreement with a theoretical estimate of $\frac{1}{8}$. The effect of this result on the decay constants of K^{40} is discussed.

INTRODUCTION

A NUMBER of investigators[1–5] have searched for positron emission from K^{40}. The most nearly definitive result was obtained by Tilley and Madansky[5] who reported an upper limit of $(1.3\pm0.7)\times10^{-5}$ on the ratio of positron to negatron emission. In their experiments a large scintillation crystal of KI (natural abundance) which served as both the source and positron detector was placed between two NaI(Tl) scintillation counters which detected annihilation quanta. Pair production in the KI crystal by the 1.46-Mev gamma of K^{40} set the ultimate limit to their detection sensitivity. With potassium highly enriched in K^{40} readily available it seemed worthwhile to repeat their experi-

† Based on work performed under the auspices of the U. S. Atomic Energy Commission.

[1] P. R. Bell and J. M. Cassidy, Phys. Rev. **77**, 409 (1950).

[2] P. R. Bell and J. M. Cassidy, Phys. Rev. **79**, 173 (1950).

[3] S. A. Colgate, Phys. Rev. **81**, 1063 (1951).

[4] M. L. Good, Phys. Rev. **81**, 1058 (1951).

[5] D. R. Tilley and L. Madansky, Phys. Rev. **116**, 413 (1959).