Magnetic Pair Spectrometer Studies of Electromagnetic Transitions in C^{14} and N^{14}†

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An intermediate-image pair spectrometer was used to study electromagnetic transitions in C^{14} and N^{14}. Energy levels in these nuclei were populated by means of the $C^{13}(d,p)C^{14}$ and $C^{13}(d,n)N^{14}$ reactions with deuteron energies between 1.9 and 3.1 MeV. In C^{14} a 6.58-MeV transition was observed in the internal pair spectrum but not in the external pair spectrum. From this a definite assignment of $J^{\pi}=0^{+}$ can be made for the C^{14} 6.58-MeV level. In N^{14} the branching ratios of the $5.69 \rightarrow 0$ and $5.69 \rightarrow 2.31$ transitions were determined to be $37\pm2\%$ and $63\pm2\%$, respectively. The energy differences between close-lying pair lines were measured with sufficient accuracy to allow limits to be placed on the lifetimes of some states in C^{14} and N^{14}. Thus, it was determined that the mean lifetime of the C^{14} 6.58-MeV level is greater than 4×10^{-13} sec.

I. INTRODUCTION

In the preceding paper[1] a report was given on investigations of the electromagnetic transitions from $Be^{9}+d$ using the Brookhaven intermediate-image pair spectrometer.[2–4] This paper describes investigations of electromagnetic transitions from $C^{13}+d$ reactions for deuteron energies between 1.9 and 3.1 MeV using the same spectrometer. For these deuteron energies transitions are expected from the reactions $C^{13}(d,p)C^{14}$ ($Q=5.947$ MeV), $C^{13}(d,n)N^{14}$ ($Q=5.319$ MeV), and $C^{13}(d,\alpha)B^{11}$ ($Q=5.167$ MeV). These transitions have been studied[5] rather thoroughly in the past. The major purpose of the present work was to search for a ground-state transition from the C^{14} 6.58-MeV level which has not been reported previously.

In the preceding paper[1] a lower limit was placed on the mean lifetime of the Be^{10} 6.18-MeV level by a measurement of the energy separation of the pair lines corresponding to the Be^{10} $5.96 \rightarrow 0$ and $6.18 \rightarrow 0$ transitions. The limit was placed from a knowledge of the Doppler shift of the Be^{10} $5.96 \rightarrow 0$ transition[6] and the measured[5] energy separation of the Be^{10} 5.96- and 6.18-MeV levels. Another purpose of the present investigation was to see to what extent this method could be applied to close-lying pair lines in the $C^{13}+d$ spectrum in order to gain information concerning lifetimes of levels in C^{14} and N^{14}.

II. EXPERIMENTAL METHODS AND RESULTS

The internal pair-line spectrum from the bombardment of a self-supporting 66% C^{13} target,[7] 0.67 ± 0.1 mg/cm² thick, with 2.7-MeV deuterons was observed in survey runs with spectrometer resolutions of 3 and 2%. The results for transitions with energies greater than 3 MeV and for 2% resolution are shown in Fig. 1. The two C^{13} pair lines shown in Fig. 1 are from the $C^{12}(d,p)C^{13}$ reaction. All the other pair lines are assigned to $C^{13}+d$ reactions.

A. The Spin-Parity of the C^{14} 6.58-MeV Level

All the transitions labeled in Fig. 1 have been reported previously[5] except the C^{14} $6.58 \rightarrow 0$ transition. It was suspected that the C^{14} 6.58-MeV level has $J^{\pi}=0^{+}$.[8] This assignment would explain why the $6.58 \rightarrow 0$ transition is observed in the pair-line spectrum of Fig. 1, since an $E0$ transition to the 0^{+} C^{14} ground state would be enhanced a factor of about 500 relative to El and Ml ($l\geq1$) transitions,[9] whereas it has not been observed in investigations of the gamma rays from $C^{13}+d$.

One way of establishing that a high-energy transition is an electric monopole is to compare the internal and

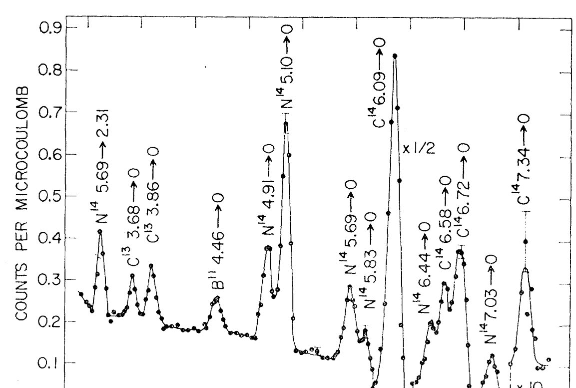

FIG. 1. Magnetic lens pair spectrum for $C^{12,13}+d$ at $E_d=2.7$ MeV. The pair lines are identified by the nucleus and the energy levels (in MeV) to which they are assigned. The resolution (full width at half-maximum) for this spectrum is 2%.

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7 The C^{13} target was kindly supplied by B. Cohen of the University of Pittsburgh.
8 E. K. Warburton, Phys. Rev. **113**, 595 (1959).
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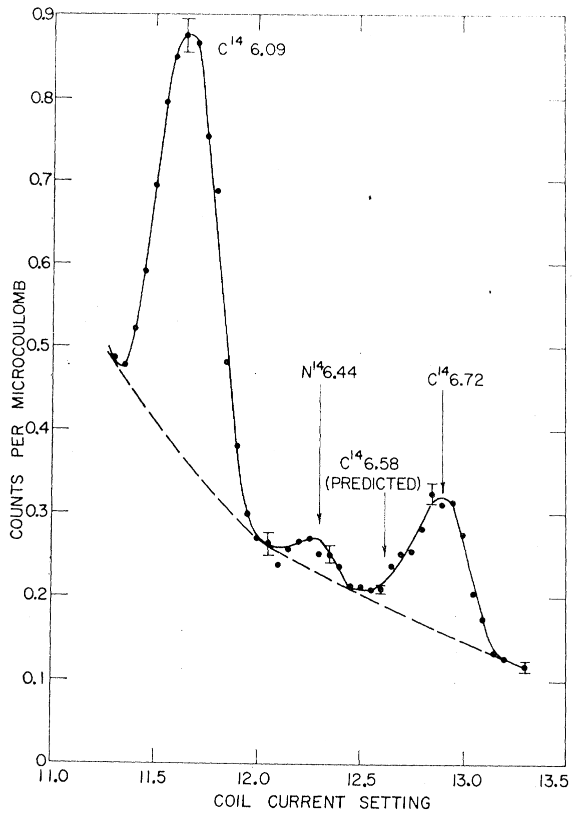

FIG. 2. External pair spectrum for $C^{13}+d$ at $E_d=3.0$ MeV. The external pair lines, all of which correspond to ground-state transitions, are identified by the nucleus and level to which they are assigned. The predicted position of the missing C^{14} 6.58 → 0 external pair line is indicated.

external pair-line spectra. The fact that gamma-ray emission is strictly forbidden for $0^+ \rightarrow 0^+$ transitions means that no line should appear in the external pair spectrum. This scheme has been used in a magnetic pair spectrometer by Bent, Bonner, and McCrary[10] as a means of establishing that the radiation from the 3.35-MeV first excited state of Ca^{40} is E0.

For our external conversion pair-line measurements the target was located in a brass cup of 3-mm i.d. into which a small amount of aquadag was first deposited. While the aquadag was still wet several flakes of the enriched C^{13} target material were pressed into the bottom of the cup where they were held firmly in place after the aquadag had dried. A 0.001-in. thick uranium converter foil 4.5 mm in diameter was cemented on the outside of the cup and the entire assembly was placed in the spectrometer such that the U-converter foil was at the normal source position. A defining aperture allowed a 2-mm diam beam to enter the cup.

Figure 2 shows the external conversion pair-line spectrum taken at approximately the same resolution setting as for the internal pair conversion spectrum of Fig. 1. These data were for $E_d=3.0$ MeV and a beam current of 1 μA. It is clear from a comparison of Figs. 1 and 2 that the relative intensities of the 6.09-, 6.44-, and 6.72-MeV lines in the external conversion spectrum are approximately the same as they are in the internal conversion spectrum whereas the 6.58-MeV line is missing in the external conversion spectrum. Its expected position is indicated by the arrow in Fig. 2.

In separate tests it was shown that the internal pair conversion yield ratio of the 6.58- and 6.72-MeV lines remained approximately constant from $E_d=2.7$ MeV to $E_d=3.0$ MeV. Thus, even allowing for the somewhat greater effective thickness of the target in the run on the external pair-line spectra a valid comparison of the 6.58- and 6.72-MeV lines can be made by using Figs. 1 and 2.

From Fig. 2 we estimated the minimum intensity of a 6.58-MeV external pair peak which could have been seen well outside of statistics. The ratio of such a peak to the intensity of the 6.72-MeV peak was then compared with the measured ratio of the 6.58- and 6.72-MeV lines in the internal pair spectrum of Fig. 1. Since the 6.72-MeV transition[5] is most probably $E3$ and since the spectrometer efficiency has been calculated[9,1] for all multipoles we can place a lower limit on the internal-pair conversion coefficient of the 6.58-MeV transition based on the 6.72-MeV transition. A simple calculation shows the number of 6.58-MeV pairs per gamma ray is >2.4 times what it would be if the transition were $E1$. A larger inequality results for any other multipolarity assignment except $E0$. Similar arguments can be made assuming that the C^{14} 6.72-MeV level is 2^-, which is the alternative to the most probable assignment of 3^-.[5] Thus, the only possible assignment to the 6.58-MeV transition is $E0$ which at once requires that the 6.58-MeV state of C^{14} have a spin-parity of 0^+.

B. The B^{11} 5.04 → 0 Transition

In addition to the survey runs taken at 2% and 3% resolution, some of the pair lines were studied at a resolution of 1.3%. The results for $E_d=2.7$ MeV are shown in Fig. 3. The presence of a pair line which we associate with the B^{11} 5.04 → 0 transition was revealed by the results shown in Fig. 4.

The pair-line shape for a given resolution setting of the spectrometer is highly energy insensitive and so for the lines of Fig. 3 the expected shape is quite accurately known. The pair lines of Fig. 3 all have shapes in agreement with that expected except the N^{14} 5.10 → 0 line which has an asymmetry on the low-energy side which indicates the presence of an unresolved pair line corresponding to a transition energy of about 5.05 MeV. The evidence for this pair line is illustrated in Fig. 4 which is an expanded plot of the N^{14} 4.91-5.10 doublet shown in Fig. 3.

The expected shape of the N^{14} 5.10 → 0 pair line is shown as well as the best fit to the experimental points.

[10] R. D. Bent, T. W. Bonner, and J. H. McCrary, Phys. Rev. 98, 1325 (1955).

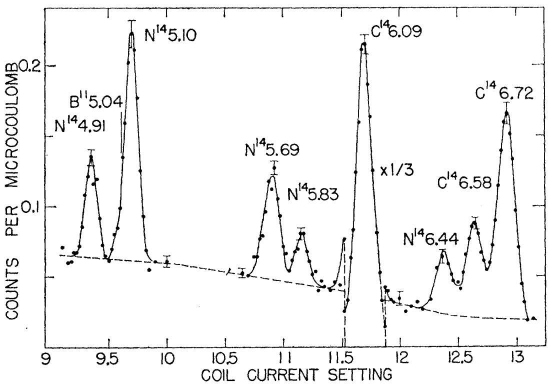

FIG. 3. Magnetic lens pair spectrum for $C^{13}+d$ at $E_d=2.7$ MeV. The pair lines, all of which correspond to ground-state transitions, are identified by the nucleus and level to which they are assigned. The resolution for this spectrum is 1.3%.

A smooth curve was drawn through the difference between these two curves with the condition that the pair line constructed in this manner have the expected resolution (1.34%) and an energy of 5.047 MeV. This energy[5] is that expected for the B^{11} 5.04 $\rightarrow$ 0 transition (5.035$\pm$0.008 MeV) with an assumed Doppler shift of 12 keV. Since the B^{11} 4.46-MeV level is excited by the $C^{13}(d,\alpha)B^{11}$ reaction at $E_d=2.7$ MeV (see Fig. 1), it seems likely that the B^{11} 5.04-MeV level also will be excited. Thus, we assign the pair line with a nominal energy of 5.05 MeV to the B^{11} 5.04 $\rightarrow$ 0 transition which has been observed previously by other reactions[5] but not by the $C^{13}(d,\alpha)B^{11}$ reaction.

C. The N^{14} 7.03 $\rightarrow$ 0 Transition

The pair line ascribed to the N^{14} 7.03 $\rightarrow$ 0 transition in Fig. 1 could be due, in whole or part, to the C^{14} 7.01 $\rightarrow$ 0 transition. In an attempt to ascertain the relative contribution of these two possibilities the energy of the pair line was measured relative to that of the C^{14} 6.72 $\rightarrow$ 0 transition with 1.3% resolution at $E_d=3.1$ MeV. The energy separation between the C^{14} 6.72-MeV line and the 7.03-MeV line was measured to be 315$\pm$13 keV. The excitation energies of the C^{14} levels below 8 MeV have been measured by means of the $C^{12}(t,p)C^{14}$ reaction.[11] From these results an energy separation between the C^{14} 6.72- and 7.01-MeV levels of 283$\pm$5 keV is obtained.[12] The C^{14} 6.72-MeV level has an attenuated Doppler shift due to the fact that it is relatively long-lived ($\tau>3\times10^{-13}$ sec).[13] The Doppler shift of the 6.72 $\rightarrow$ 0 transition was measured at $E_d=2.9$ MeV to be 2$\pm$4 keV between 0° and 90° to the beam.[13] For the present conditions this corresponds to a Doppler shift of 1.2$\pm$2.4 keV. Thus, if the 7.03-MeV pair line is due to the C^{14} 7.01-MeV transition it has a Doppler shift of 33$\pm$14 keV which is reasonable since a Doppler shift of 35 keV would result for a lifetime short compared to 10^{-13} sec and for an isotropic distribution of the protons in the center-of-mass system.

The measured excitation energy of the C^{14} 6.724-MeV level has an uncertainty of 7 keV,[5] and thus the measurement of the energy separation of the C^{14} 6.72- and the 7.03-MeV pair lines yields 7.040$\pm$0.015 MeV for the energy of the latter. The excitation energy of the N^{14} 7.03-MeV level has recently been measured to be 7.032$\pm$0.010 MeV.[14] Thus, if the 7.03-MeV pair line is due to the N^{14} 7.03 $\rightarrow$ 0 transition it has a Doppler shift of 8$\pm$18 keV which again is reasonable. We conclude that the energy measurement of the 7.03-MeV pair line is consistent with it being due to the C^{14} 7.01 $\rightarrow$ 0 transition, the N^{14} 7.03 $\rightarrow$ 0 transition, or both.

The threshold for the $C^{13}(d,p)C^{14}$ (7.01-MeV level) reaction is 1.225 MeV while that for the $C^{13}(d,n)N^{14}$ (7.03-MeV level) reaction is 1.975 MeV. Because of the difference between these thresholds it was felt that an excitation curve for the 7.03-MeV transition might shed some light on its origin. An excitation curve was measured at 3% spectrometer resolution. The result is shown in Fig. 5. The cross section scale in Fig. 5 has an uncertainty of 50% which is mainly due to uncertainties in the target density as explained in Sec. IID. An apparent threshold very close to that expected for the $C^{13}(d,n)N^{14}$ (7.03-MeV level) reaction (1.975 MeV) is indicated by the excitation curve of Fig. 5. No evidence of the 7.03-MeV transition was seen for deuteron energies less than this energy. Thus, the excitation curve suggests that the

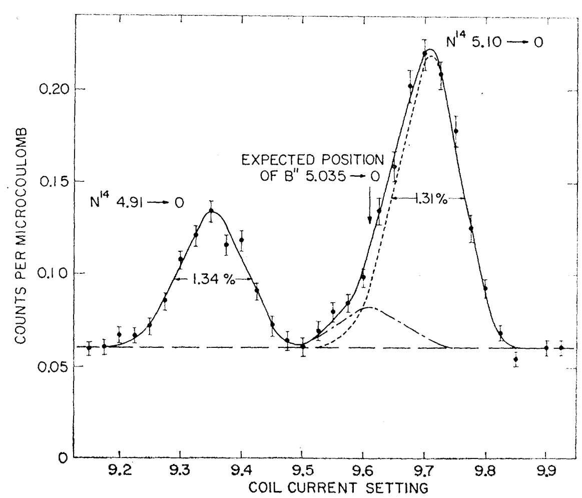

FIG. 4. Detail of the N^{14} 4.91 $\rightarrow$ 0 and 5.10 $\rightarrow$ 0 doublet of Fig. 3 showing the evidence for a B^{11} 5.035 $\rightarrow$ 0 transition. The decomposition of the experimental data into three pair lines is indicated. The difference in resolution between the N^{14} 4.91 $\rightarrow$ 0 and N^{14} 5.10 $\rightarrow$ 0 pair lines takes into account the expected difference in the Doppler broadening of these two lines.

[11] A. A. Jaffe, F. De S. Barros, P. D. Forsyth, J. Muto, I. J. Taylor, and S. Ramavataram, Proc. Phys. Soc. (London), **76**, 914 (1960).

[12] A. A. Jaffe (private communication).

[13] E. K. Warburton and H. J. Rose, Phys. Rev. **109**, 1199 (1958).

[14] D. D. Clayton, Phys. Rev. **128**, 2254 (1962).

7.03-MeV pair line is mainly due to the N^{14} 7.03 → 0 transition; although the possibility that the pair line is due to the C^{14} 7.01 → 0 transition cannot be ruled out from this evidence since it is possible (but unlikely) that the Coulomb barrier strongly suppresses the (d,p) reaction from its threshold (1.225 MeV) to about 1.975 MeV. The resonance, apparent at about 2.2 MeV in Fig. 5, has a measured width of 130±40 keV and appears at an energy (after correction for target thickness) of 2.21±0.03 MeV. The target thickness at this energy is 160±25 keV so that the measured width is due mainly to the target thickness and is larger than the resonance width. Resonances for $C^{13}+d$ have been reported[5] at 2.20±0.01 and 2.23±0.02 MeV with widths of 22±4 and ~50 keV, respectively. The resonance of Fig. 5 could be due to either of these.

D. $C^{13}+d$ Cross Sections at $E_d=2.7$ MeV

The transitions observed in the various pair line spectra taken at deuteron energy of 2.7 MeV are listed in Table I. Peak intensities which correspond to 2% resolution (Fig. 1) are averages of all the data taken at 2.7 MeV. For the 3 and 1.3% resolution spectra peak intensities were converted to those for 2% resolution by using the known relation between spectrometer resolution and transmission.[2] By means of the procedure given in the preceding paper[1] the peak intensities were converted to cross sections. The C^{13} target used for this work had an observably nonuniform thickness and several cracks developed in mounting; therefore, the effective target thickness was estimated and the absolute cross section scale of the Table I is assigned an uncertainty of 50%.

The spin-parity and multipolarity assignments are in our judgment the most probable values. If a multipolarity assignment is wrong, then the cross section will be also, since the spectrometer efficiency is dependent on the multipolarity of the transition.[1,9] All transitions are assumed to proceed by the lowest multipolarity possible except the N^{14} 5.83 → 0 transition which has

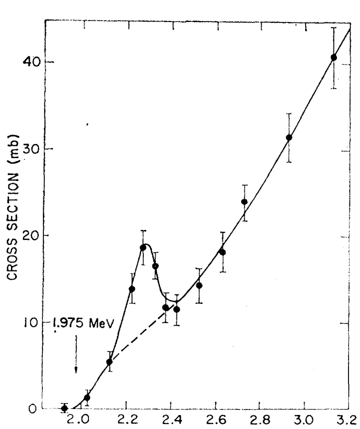

FIG. 5. Excitation curve for the 7.03-MeV pair line observed in $C^{13}+d$. The cross section scale has an uncertainty of 50%. The threshold of 1.975 MeV for the $C^{13}(d,n)N^{14}$ (7.03-MeV level) reaction is indicated.

TABLE I. Results for electromagnetic transitions from $C^{13}+d$.

Transition	Peak intensity (counts/μC)	Assumed spin-parity and multipolarity	Cross section[a] (mb)
N^{14} 5.69 → 2.31	0.213±0.009	1^-: $E1$	63.4
B^{11} 4.46 → 0	0.097±0.007	$\frac{5}{2}^-$: $M1$	28.0
N^{14} 4.91 → 0	0.26 ±0.02	0^-: $E1$	54.4
B^{11} 5.04 → 0	0.08 ±0.03	$\frac{3}{2}^-$: $M1$	20.1
N^{14} 5.10 → 0	0.55 ±0.02	2^-: $E1$	113.0
N^{14} 5.69 → 0	0.186±0.007	1^-: $E1$	37.2
N^{14} 5.83 → 0	0.10 ±0.01	3^-: $M2+E3$	25.2
C^{14} 6.09 → 0	1.65 ±0.03	1^-: $E1$	330.0
N^{14} 6.44 → 0	0.17 ±0.01	3^+: $E2$	37.3
C^{14} 6.58 → 0	0.21 ±0.01	0^+: $E0$	0.12
C^{14} 6.72 → 0	0.40 ±0.02	3^-: $E3$	94.5
N^{14} 7.03 → 0	0.10 ±0.02	2^+: $M1$	23.2
C^{14} 7.34 → 0	0.027±0.006	2^-: $M2$	6.44

[a] Average value for $E_d=2.7$ to 2.56 MeV. The absolute cross-section scale has an estimated accuracy of 50%. The relative cross sections have an uncertainty which is a combination of that in the peak intensities, 3% in the relative efficiencies and, unless otherwise stated in the text, 10% due to the possible effects of anisotropic emission of the pairs (see Ref. 1).

been found[15] to be a nearly equal mixture of quadrupole and octupole. An equal mixture of $M2$ and $E3$ was taken for this transition.

The spectrometer efficiency used was that appropriate to nonaligned nuclei.[9] For several reasons, no attempt was made to correct for alignment effects using the procedure of the preceding paper.[1] Firstly, the experimental evidence on the anisotropies of the γ rays accompanying the internal pairs of Table I is quite scanty. Second, the results given in the preceding paper[1] indicate that corrections larger than about 10% are unlikely and this is small compared to the 50% uncertainty in the cross section scale of Table I.

E. Branching Ratios of the N^{14} 5.69-MeV Level

The N^{14} 5.69 → 2.31-MeV transition is the only cascade shown in Fig. 1. Transitions from the N^{14} 5.69-MeV level to N^{14} states other than the ground state and first excited state have not been observed[5] and assuming that other decay modes have negligible intensities, the branching ratios of these two transitions can be obtained from the data of Table I. The result is 37±2 and 63±2% for the 5.69 → 0 and 5.69 → 2.31 transitions, respectively. This result is in good agreement with previous determinations of these branching ratios.[5] In obtaining this result both transitions were taken to be $E1$ in agreement with the result of recent experiments,[16] and with the $J^\pi=1^-$ assignment to the N^{14} 5.69-MeV level demanded by $C^{13}(d,n)N^{14}$ angular distribution meaurements[17] and earlier works.[5] Angular distribution measurements of James[17] show that the N^{14} 5.69-MeV level is formed predominantly by the stripping

[15] E. K. Warburton, H. J. Rose, and E. N. Hatch, Phys. Rev. **114**, 214 (1959).
[16] E. K. Warburton, D. E. Alburger, A. Gallmann, P. Wagner, and L. F. Chase, Jr., (to be published).
[17] A. N. James, Nucl. Phys. **124**, 132 (1961).

reaction with the capture of an $l_p=0$ proton. For this reaction mechanism the gamma-ray transitions from the 5.69-MeV level must be isotropic. For this reason the uncertainty in the branching ratios due to possible alignment of the 5.69-MeV level was assumed to be negligible.[1] In addition, the correction for alignment effects is quite small in the case of $E1$ transitions.[1]

F. Doublet Separations and Lifetime Limits

The main motivation for obtaining the 1.3% resolution pair-line spectra of Fig. 3 was to measure the energy separation between the close-lying pair-line doublets: N^{14} 4.91–5.10, N^{14} 5.69–5.83, C^{14} 6.09–6.58, and C^{14} 6.58–6.72. The data were taken in such a manner as to minimize the error in the determination of these doublet separations. For instance, the data for the N^{14} 4.91–5.10 doublet (Fig. 4) were taken by increasing the coil current in steps between settings of 9 and 10, repeating the same steps in reverse order, and finally, rerunning the doublet in increasing steps from 9 to 10. By this means, it was hoped to minimize any errors in the energy separation due to shifts of the spectrometer calibration. The pair-line spectra of other doublets were obtained in the same manner except that the C^{14} 6.09–6.58–6.72 triplet was run as a sequence. For the N^{14} 4.91–5.10 and 5.69–5.83 doublets occasional checks were run on the C^{14} 6.09 $\rightarrow$ 0 pair line and it was found that, as suspected, there were small shifts in the spectrometer calibration. The data for the N^{14} 6.44 $\rightarrow$ 0 pair line were taken separately.

From these data the energy separations given in Table II were obtained. Also shown in Table II are the

TABLE II. Energy differences of the pair-line doublets observed at $E_d=2.7$ MeV with 1.3% resolution.

Doublet	Pair line separation (keV)	Excitation separation (keV)	Relative Doppler shift (keV)
N^{14} 4.91–5.10	177±4	192±5[a]	+15±6.4
N^{14} 5.68–5.83	129±4.5	145±2[a]	+16±5
C^{14} 6.09–6.58	477±4.8	495±5[b]	+18±7
C^{14} 6.09–6.72	622±4	636±5[b]	+14±6.4
C^{14} 6.58–6.72	146±4.8	141±5[b]	−5±7

[a] References 18 and 19.
[b] References 11 and 12.

best determinations[11,12,18,19] of the energy separations of the excitation energies of the emitting levels and the differences between the pair-line separations and the excitation energy separations. The latter gives the relative Doppler shifts of the doublets (that of the lower energy line minus that of the higher energy line) and thus can be used, in principle, to give information on the relative lifetimes of the doublets.

The N^{14} 4.91–5.10-MeV Doublet

The Doppler shift of the N^{14} 5.10 $\rightarrow$ 0 transition has been measured[15] previously to be (0.1±0.1) times the shift expected for a lifetime very short compared to 10^{-13} sec. From this measurement a limit $\tau>3\times10^{-13}$ sec was set for the lifetime of the N^{14} 5.10-MeV level. For the condition of the present experiment this corresponds to a Doppler shift of 2±2 keV assuming an isotropic distribution of the recoiling nuclei in the center-of-mass system (this latter assumption cannot introduce appreciable error). Combining this result with the relative shift given in Table II gives 17±7 keV for the Doppler shift of the N^{14} 4.91 $\rightarrow$ 0 transition. From preliminary results[20,21] for $C^{13}(d,n)N^{14}$ angular distributions we estimate 20±2 keV for the expected shift[1] of the 4.91 $\rightarrow$ 0 transition under the conditions of the present experiment if the lifetime of the N^{14} 4.91-MeV level is very short compared to the stopping time of the N^{14} recoils. Thus, we have an attenuation factor[6] F of 0.85±0.35 where $F=(\alpha/\tau)/(1+\alpha/\tau)$. The stopping power α for N^{14} ions in carbon can be obtained from the stopping power data of Porat and Ramavataram.[22] The result is $\alpha=(4.6\pm0.5)\times10^{-13}$ sec, in which case we obtain the 67% confidence limit $\tau<5\times10^{-13}$ sec for the mean lifetime of the N^{14} 4.91-MeV level. There has been no previously published information on this lifetime.

The N^{14} 5.69–5.83 MeV Doublet

There is no information on the angular distributions of the $C^{13}(d,n)N^{14}$ reactions leading to either the 5.69-or 5.83-MeV level in the deuteron range of 2.5–3 MeV. However, the angular distribution leading to the 5.69-MeV level is quite similar to that of the 4.91-MeV level at $E_d=1.2$ MeV,[17] and we assume these two distributions are roughly similar at $E_d=2.7$ MeV. This assumption seems reasonable since both levels are formed by $l=0$ stripping patterns at $E_d=1.2$ MeV and the 5.69-MeV level should be formed by $l=0$ stripping at higher energies as is the 4.91-MeV level.[20,21] Since the 5.69 $\rightarrow$ 2.31 transition is an allowed $E1$ transition we also assume that the N^{14} 5.69-MeV level has a lifetime short compared to 10^{-13} sec. With these assumptions we obtain 25±5 keV for the Doppler shift of the N^{14} 5.69 $\rightarrow$ 0 transition under the conditions of the present experiment. The large uncertainty reflects our inexact knowledge of the (d,n) angular distribution. Combining this result with the relative shift listed in Table II gives 9±7 keV for the Doppler shift of the N^{14} 5.83 $\rightarrow$ 0 transition. The expected full shift of the 5.83 $\rightarrow$ 0 transition is 30 keV for an isotropic distribution of the recoiling nuclei. We assume 30% uncertainty to cover devia-

[18] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **75**, 745 (1960).
[19] H. Marchant (private communication).
[20] F. J. Vaughn, L. F. Chase, Jr., and R. G. Johnson, Bull. Am. Phys. Soc. **5**, 404 (1960).
[21] L. F. Chase, Jr. (private communication).
[22] D. I. Porat and K. Ramavataram, Proc. Phys. Soc. (London) **77**, 97 (1961).

tions from isotropy and obtain the estimate $F=0.3\pm0.3$ for the attenuation factor for the N^{14} 5.83-MeV level. This is to be compared to the previous determination[15] of $F=0.67\pm0.09$ for stopping in carbon. The present result is in slight disagreement with the previous result (such as to indicate a larger lifetime) but the uncertainty is too large to allow a conclusion to be drawn.

The C^{14} 6.58-MeV Level

The relative and absolute Doppler shifts of the C^{14} $6.09\rightarrow0$ and $6.72\rightarrow0$ transitions have been measured previously for 2.9-MeV deuterons incident on carbon.[13] Assuming the angular distributions of the recoiling C^{14} nuclei are the same at $E_d=2.9$ and 2.7 MeV, these previous measurements yield 16 ± 3 keV for the relative Doppler shift (that of the 6.09-MeV line minus that of the 6.72-MeV line) for the conditions of the present measurements. This is in good agreement with the present result of 14 ± 6.4 keV and serves as a check on our method. Absolute Doppler shifts for the present conditions of 16 ± 2 and 1.4 ± 2.7 keV for the $6.09\rightarrow0$ and $6.72\rightarrow0$ transitions are also inferred from the previous work. Combining these values with the relative Doppler shifts of Table II gives the Doppler shift of the C^{14} $6.58\rightarrow0$ transition as -2 ± 7 and -3.7 ± 7.5 keV from the values for the 6.09–6.58 and 6.58–6.72 separations, respectively. We adopt -3 ± 7 keV for the Doppler shift of the C^{14} $6.58\rightarrow0$ transition. The Doppler shift expected for an isotropic distribution of the outgoing protons and a lifetime short compared to the stopping time of the recoiling nuclei is 34 keV. The minimum possible shift, corresponding to all the protons being emitted at 0°, is 14.2 keV for $\tau\ll10^{-13}$ sec. For $\tau\ll10^{-13}$ sec a Doppler shift less than 22 keV would be quite unlikely since it would correspond to sharply forward peaking of the angular distribution. Thus, if we increase the experimental Doppler shift by two standard deviations we obtain $F=11/22=0.5$, and we adopt the limit $F<0.5$ for the C^{14} $6.58\rightarrow0$ transition. The stopping time, α, for C^{14} ions in carbon can be obtained from the stopping power data of Porat and Ramavataram.[22] The result is $(5.2\pm0.5)\times10^{-13}$ sec and using $F=(\alpha/\tau)/(1+\alpha/\tau)$ we obtain the limit $\tau>4\times10^{-13}$ sec for the mean lifetime of the C^{14} 6.58-MeV level.

III. DISCUSSION

The C^{14} 6.58-MeV level was first observed in the $C^{13}(d,p)C^{14}$ reaction at $E_d=14.8$ MeV,[23] and it was reported that the proton angular distribution was fitted by the Butler formula with a mixture of $l_n=0$ and 2. If true, this would demand that $J^\pi=1^-$. However, the stripping radius used was too large and it was later found[13] that $l_n=2$ or a mixture of $l_n=1$ and 3 gave the best fits to the angular distribution but that neither fit was particularly good so that a tentative assignment of $J^\pi=1^-$, $2^\pm$, or 3^- was made for the C^{14} 6.58-MeV level. Later, $C^{12}(t,p)C^{14}$ angular distributions were obtained for the bound C^{14} levels,[11] and interpreted by the double-stripping theory. It was found that $J^\pi=1^-$ or 0^+ gave the only acceptable agreement with double-stripping theory and since the (d,p) results indicated $J^\pi=1^-$, $2^\pm$, or 3^- the 1^- assignment was adopted. However, the 0^+ assignment should not have been excluded since the $J^\pi=1^-$, $2^\pm$, or 3^- assignment was only tentative. We conclude that the present assignment of $J^\pi=0^+$, which has been verified in a later experiment,[16] is in good agreement with the double-stripping results[11] and that the simple plane-wave stripping theory is not adequate to explain the (d,p) stripping results.[23]

It was conjectured earlier[8,24] that the C^{14} 6.58-MeV level was $J^\pi=0^+$ since it is the only known C^{14} level which could reasonably be the analog of the N^{14} $T=1$, 0^+ 8.62-MeV level. Now that the C^{14} 6.58-MeV level has been established as $J^\pi=0^+$ an identification with the N^{14} 8.62-MeV level can be taken as definite.

It has been proposed[15,24] that a fairly good description of the 1^-, C^{14} 6.09- and 0^+, 6.58-MeV levels (or the N^{14} 8.06- and 8.62-MeV levels) is $p_{1/2}2s_{1/2}$ outside an inert zero-spin C^{12} core in the first case and two particles in the $(1d,2s)$ shell outside an inert zero spin C^{12} core in the second case. Unna and Talmi[25] predicted the excitation energies of these two levels (in N^{14}) with better than 200 keV accuracy using a model of $(p_{1/2}2s_{1/2})$ and $(2s_{1/2}{}^2)$ outside a $1s_{1/2}{}^4p_{3/2}{}^8$ core. We can use this model to calculate the transition strength of the $E1$ C^{14} $6.58\rightarrow6.09$ transition. The result is, in the notation used by Warburton and Pinkston,[24] $\Lambda(E1)=1.92$ corresponding to $\Gamma_\gamma=1.4\times10^{-2}$ eV or a mean lifetime of 4.8×10^{-14} sec. Since this partial lifetime is about 10^3–10^4 times shorter than the expected lifetime[1] of the $E0$ C^{14} $6.58\rightarrow0$ transition it can be compared to the lifetime limit $\tau>4\times10^{-13}$ sec determined in the present work. The discrepancy of at least a factor of 10 shows that the simple model of $(p_{1/2}2s_{1/2})$ and $(2s_{1/2}{}^2)$ wave functions is not adequate to explain the lifetime of the C^{14} 6.58-MeV level. The calculated lifetime can be reduced by a factor of 10 or more by taking the expected admixtures of $(p_{1/2}d_{3/2})$ in the C^{14} 6.09-MeV level and $p_{1/2}{}^2$ and (d^2) in the C^{14} 6.58-MeV level in the right proportion; however, the high degree of cancellation necessary to cause this reduction seems artificial and improbable so that a more plausible "fixing up" of the wave functions would seem to demand a breaking up of the inert zero-spin C^{12} core. It may well be that the 0^+, C^{14} 6.58-MeV level has as complicated a shell-model wave function as the 0^+ states of C^{12} at 7.65 MeV and O^{16} at 6.06 MeV seem to have.

It was stated in Sec. II C that the excitation curve of Fig. 5 favored an assignment of the 7.03-MeV pair line

[23] J. N. McGruer, E. K. Warburton, and R. S. Bender, Phys. Rev. **100**, 235 (1955).

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

[25] I. Unna and I. Talmi, Phys. Rev. **112**, 452 (1958).

to the N^{14} 7.03 → 0 transition rather than to the C^{14} 7.01 → 0 transition. Further evidence for this assignment is that the N^{14} 7.03-MeV is known to be excited by the $C^{13}(d,n)N^{14}$ reaction at $E_d=3.9$ MeV,[26] and is known to decay predominantly by a ground-state transition.[5] On the other hand, the C^{14} 7.01-MeV level was not observed in a study of the $C^{13}(d,p)C^{14}$ reaction at $E_d=14.8$ MeV,[23] while all the other bound levels were. Although no quantitative numbers are available we can say that at $E_d=14.8$ MeV the C^{14} 7.01-MeV level must be quite weakly excited compared to the other C^{14} levels. Insofar as the $C^{13}(d,p)C^{14}$ reaction proceeds by the stripping mechanism, the same should be true at lower deuteron energies and this is inconsistent with the rather large cross section (see Fig. 5) observed for the 7.03-MeV pair line. If, however, the C^{14} 7.01-MeV level has $J^\pi=0^+$ and the 7.03-MeV pair line were due to a ground state transition from this level, the cross section for the 7.03 → 0 transition would be about 500 times less[9] and the above remarks would not apply. A 0^+ assignment was made to the C^{14} 7.01-MeV level from a fit to the $C^{12}(t,p)C^{14}$ angular distribution,[11] but we believe this assignment should not be taken as definite and, in fact, there is strong indirect evidence that the C^{14} 7.01-MeV level is $J^\pi=2^+$. An $L=0$ (and thus $J^\pi=0^+$) double-stripping pattern gives the best fit to the $C^{12}(t,p)C^{14}$ (7.01-MeV level) reaction[11] with an $L=2$ (and thus $J^\pi=2^+$) pattern giving the second best fit.[12] The $L=2$ pattern fits the maximum of the angular distribution but has a larger half-width than the experimental data. In view of the possibilities for distortion and the lack of agreement between the simple double-stripping theory and experiment in many cases,[27] we feel that the double-stripping results cannot be taken to give a strong preference for $J^\pi=0^+$ over $J^\pi=2^+$. The indirect evidence for a 2^+ assignment is that the C^{14} 7.01-MeV level is the only known C^{14} level which could be the analog of the $J^\pi=2^+$, $T=1$, N^{14} 9.17-MeV level and in turn there is no other known N^{14} level which could be a $J^\pi=0^+$, $T=1$ analog of the C^{14} 7.01-MeV level. Thus, if the C^{14} 7.01-MeV level is 0^+ and not 2^+ it means there is an undetected C^{14} level (with $J^\pi=2^+$) near 7-MeV excitation and an undetected N^{14} level (with $J^\pi=0^+$) near 9.2-MeV excitation. This seems quite unlikely.

[26] R. E. Benenson, Phys. Rev. **90**, 420 (1953).
[27] See, for instance, Ref. 18.

One purpose of this investigation was to see what information could be obtained concerning nuclear lifetimes from measurement of the energy separation of close-lying pair lines. It is clear from the present results that a useful measurement of the relative Doppler shift of two lines can be obtained if the Doppler shift of one of the lines and the separation in excitation energy of the two lines are known from other work. However, the accuracy of this method is quite a bit less than in conventional Doppler shift measurements with scintillation crystal spectroscopy. The present method is of use, then, when conventional Doppler-shift techniques are not applicable. This would be true when the energy resolution of scintillation crystals was not adequate or in the study of $E0$ transitions as in the present work on the C^{14} 6.58 → 0 transition.

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$Ne^{20}(p,p'\gamma)$ Angular Correlations at Low Energy

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$Ne^{20}(p,p'\gamma)$ 1.63-MeV angular correlations have been measured in the 5.2–6.10 MeV energy range, where the elastic and inelastic excitation functions vary in a compensating manner. The measurements have been made at 5.25-, 5.55-, and 6.10-MeV proton energies, the position of the proton detector being at 60°, 90°, and 120°. One obtains strong angular correlation functions of the form $A+B\sin^2 2(\theta-\theta_0)$, where θ_0 defines the axis of symmetry. The angular correlation curves are insensitive to a change of the incident proton energy and θ_0 is situated in the proximity of the recoil direction θ_R of the nucleus. These facts could constitute an argument in favor of the direct-interaction mechanism.

I. INTRODUCTION

In the last few years the $(p,p'\gamma)$ angular correlation has been used several times for the study of reaction mechanisms at low energy.[1–8]. In these papers it is

[1] F. D. Seward, Phys. Rev. **114**, 514 (1959).
[2] H. A. Lackner, G. F. Dell, and H. J. Hausman, Phys. Rev. **118**, 1237 (1960).