MEASUREMENTS OF n-γ COINCIDENCES IN THE REACTION $^{10}B(d,n\gamma)^{11}C$†

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Summary

The energies of some neutron groups leading to low excited states of ^{11}C in the reaction $^{10}B(d,n\gamma)^{11}C$ have been measured. These lead to values of $4 \cdot 3 \pm 0 \cdot 3$ MeV and $6 \cdot 53 \pm 0 \cdot 02$ MeV for the energies of the second and fourth excited states respectively. γ-Ray spectra have also been studied in coincidence with different neutron groups. Ground state transitions were observed from the second, third, and fourth excited states, together with cascade decays of the fourth excited state through each of the second and third. Deductions from these γ-ray spectra considerably reduce the number of spin possibilities which have been found for these levels by other workers.

I. Introduction

A good deal of information about the energy levels of a nucleus can be obtained from the observation of γ-ray transitions between such levels. In the case of ^{11}C, the parities of the first few levels are known, and measurements of the relative intensities of the possible γ-ray transitions between these levels make it possible to deduce the most probable multipolarities of the γ-rays and hence to select the most probable spin values from the many alternatives which have been provided from other measurements.

The current knowledge regarding the energies, spins, and parities of the levels of ^{11}C is listed fully in the compilation of Ajzenberg-Selove and Lauritsen (1959), and the information relevant to the work described in this paper is reproduced, together with the equivalent data on the mirror nucleus ^{11}B, in Figure 1. The parities of all these levels are known to be odd from the $l_p=1$ stripping patterns found by Cerineo (1956) and Maslin, Calvert, and Jaffe (1956) for the neutron groups in the reaction $^{10}B(d,n)^{11}C$. These stripping data also restrict the spins of all these levels to 3/2, 5/2, 7/2, or 9/2, and in the case of the ground state, the β^+ decay evidence restricts the spin to 1/2, 3/2, or 5/2. The value 3/2 is considered the most likely, this being the spin of the ^{11}B ground state.

Apart from the 2 MeV γ-ray from the first excited state, the only γ-rays which have been observed from ^{11}C are those observed by Bent *et al.* (1955) and Sample *et al.* (1955) in the presence of all other γ-rays following the deuteron bombardment of ^{10}B, and the only certain assignment is the ground state

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transition from the $6 \cdot 50$ MeV state. In the work to be described below, the spectra of γ-rays involved in the decay of individual levels are examined separately, their observation being in coincidence with the emission of selected neutron groups in the $^{10}B(d,n\gamma)^{11}C$ reaction.

The situation in the mirror nucleus, ^{11}B, where the ground state spin is known to be $3/2^-$, is a little clearer. The $l_n=1$ stripping patterns found by Evans and Parkinson (1954) in the reaction $^{10}B(d,p)^{11}B$ place the same restrictions on the spins and parities of the low levels of ^{11}B as the $l_p=1$ patterns did in the case of ^{11}C, but these spin possibilities have been considerably reduced in most cases by the angular distribution and angular correlation measurements of Thirion (1953),

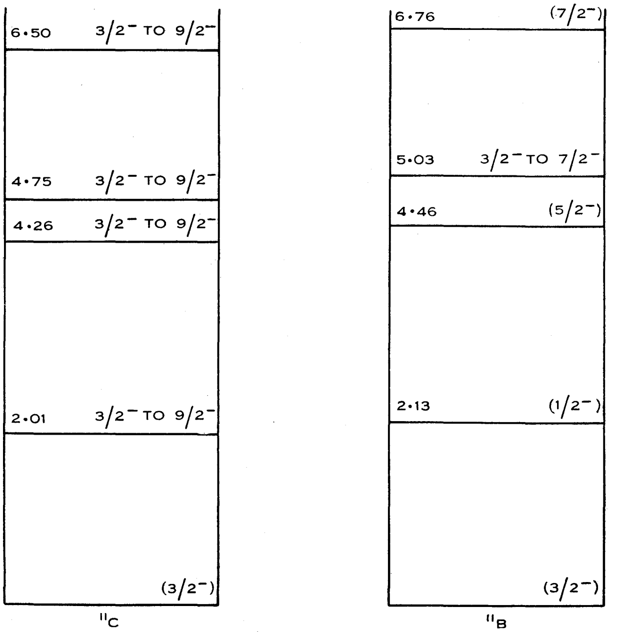

Fig. 1.—Accumulated data concerning the energies and spins of excited states of ^{11}C and ^{11}B.

Bair, Kington, and Willard (1955), and Ferguson *et al.* (1958). Of particular interest is the conclusion that the spin of the $2 \cdot 13$ MeV level is 1/2, in agreement with the intermediate coupling model, but in contradiction to the $l_n=1$ stripping data, the contradiction being resolved by Wilkinson (1957) by postulating spin flip stripping. Since the situation in the case of the $2 \cdot 01$ MeV level of ^{11}C is exactly analogous, it would be reasonable to consider spin 1/2 as a possibility for this level also.

Our experiment concerns only ^{11}C, consisting of measurements on the reaction $^{10}B(d,n\gamma)^{11}C$. Two types of measurement have been made: firstly, the energies of the neutron groups were measured by a time-of-flight method, and secondly, the γ-ray spectra in coincidence with the individual neutron groups were observed.

II. Experimental Details

A beam of deuterons from the 750 kV electrostatic generator struck a separated boron target (99 per cent. ^{10}B, supplied by A.E.R.E., Harwell) deposited on a nickel backing. Two target thicknesses were used : 90 μg cm^{-2} for the neutron energy measurements and 260 μg cm^{-2} for the γ-ray measurements. γ-Rays were detected by a NaI(Tl) crystal placed as close as possible to the target and at 90° to the direction of the deuteron beam. This crystal was coupled to an RCA 6342 photomultiplier tube. Two crystal sizes, $1\frac{1}{2}$ in. diameter by 1 in. and 3 in. diameter by 3 in. were used. The neutron detector consisted of a 3 in. diameter by $\frac{3}{4}$ in. thick cylinder of " Pamelon " plastic scintillator (manufactured by Isotope Developments Ltd.) coupled via a " Perspex " light pipe

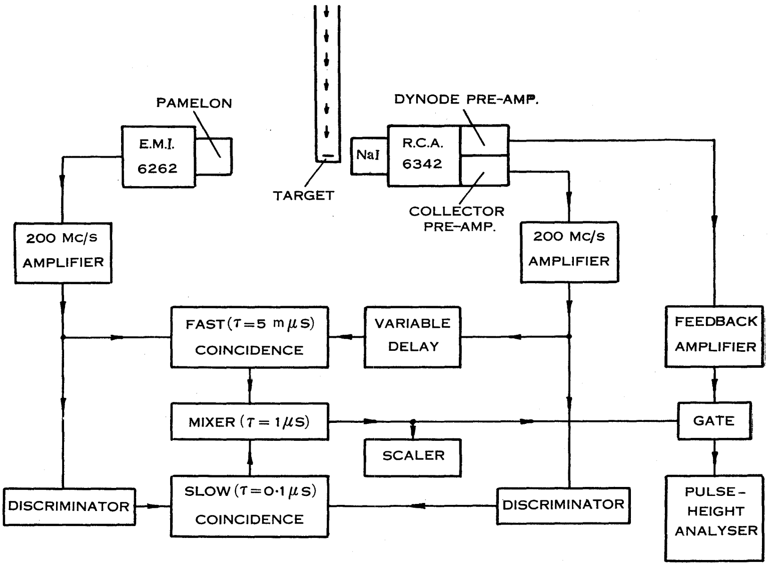

Fig. 2.—Block diagram of delayed coincidence circuit.

to an EMI 6262 photomultiplier. This counter was surrounded by a lead and paraffin wax shield with a collimator defining the directions of the fast neutrons incident on the scintillator. The whole of this assembly could be moved so that both the length and direction of the neutron flight path were easily varied.

While the neutron counter was always located in the horizontal plane containing the incident beam direction, different locations were used for the two NaI(Tl) crystals. The $1\frac{1}{2}$ by 1 in. crystal was placed with its axis in this same horizontal plane but, when the 3 by 3 in. crystal was used, it was located below the target with its axis vertical.

The block diagram (Fig. 2) shows the time-of-flight circuitry. By using the largest recommended value of the high voltage applied to the 6342 photomultiplier and a small (1200 Ω) collector load, a pulse from the γ-counter could be obtained which was fast enough to operate the fast coincidence unit (Harwell type 1153A) at its shortest resolving time of 5 mμs. With this arrangement, the delay distribution used for testing—that obtained with the counters close together and a source of ^{22}Na between them—had a width at half height of 7 mμs.

The interpretation of a delay distribution for a given neutron flight path requires a knowledge of the location, on the variable delay axis, of the " zero delay " position, i.e. the setting of the variable delay for which pulses from events in the two scintillators that are truly prompt are brought into coincidence. In our case, because of the severe differentiation of the collector pulses from the γ-counter, the rise time of these pulses varied with their magnitude. This resulted in a small variation in the inherent delay of such pulses, so that the zero delay position was dependent on the energies of the γ-rays involved in the coincidences. For this reason, it was not possible to use the position of the peak observed in the test delay distributions taken with a ^{22}Na source as the zero delay position for the (n,γ) coincidences, nor was it possible to use the position of the prompt peak in an actual run, this latter peak being contributed to by coincidences such as γ-γ cascades following ^{10}B$(d,p)^{11}$B* which involve a large range of γ energies, and " inverted " (n,γ) coincidences in which the neutron is detected in the γ-counter and vice versa. Hence the measurements of neutron energy were obtained by finding the position of the appropriate delay peak at various lengths of flight path and determining the neutron velocity from the slope of the resulting distance-time graph, all points on which were then produced by coincidences in which the same γ-ray was involved and were measured with identical circuitry. The discriminator settings in the slow coincidence circuit were chosen to eliminate, as far as possible, events due to coincidences, both random and true, other than those under observation.

III. Delay Distributions

(*a*) *The Neutron Group to the 6·50 MeV State of ^{11}C*

Delay distributions were measured at neutron directions of 0 and 90° relative to that of the incident deuteron beam and at effective deuteron energies, allowing for a mean energy loss of 20 keV in the target, of 580 and 630 keV. The neutrons of this group are of low energy (about 0·5 MeV) so that the pulses produced by them in the neutron detector were of the same order of size as the noise pulses. Thus the lowest available setting of the discriminator in the neutron channel had to be used. In the γ-channel, the discriminator was set to exclude pulses produced by electrons of energy up to 2 MeV from the ^{128}I activity in the NaI (see Section IV (*a*)), thereby favouring the detection of coincidences associated with the relatively intense 6·5 MeV radiation (Bent *et al.* 1955). In this way a true-to-random ratio of about 1 was obtained. A typical delay distribution is shown in Figure 3. Figure 4 shows the delay versus distance relationship for one set of delay distributions, and the results obtained from these measurements are shown in Table 1.

(*b*) *The Neutron Group to the 4·26 MeV State of ^{11}C*

For the 0° direction and a deuteron energy of 580 keV the neutron groups to the 2·01, 4·26, and 4·75 MeV states of ^{11}C should have energies of approximately 4·9, 2·8, and 2·3 MeV respectively, with the corresponding flight times per metre of 33, 44, and 48 mμs. With delay distributions having a width at half height of 10 mμs, rather long flight paths would be required to resolve these groups. Under these conditions the count rates in our detector would be pro-

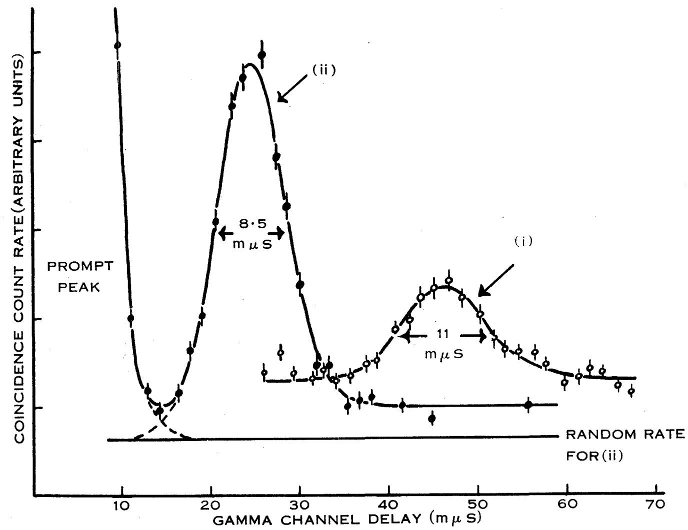

Fig. 3.—Typical delay distributions. Curve (i) neutron group to 6·50 MeV state (90° direction; flight path 33·6 cm). Curve (ii) neutron group to 4·26 MeV state (0° direction; flight path 50·8 cm). The random rate was measured by inserting a large delay in the neutron channel, and the higher count rate at large γ-channel delays is attributed to true coincidences involving scattered neutrons.

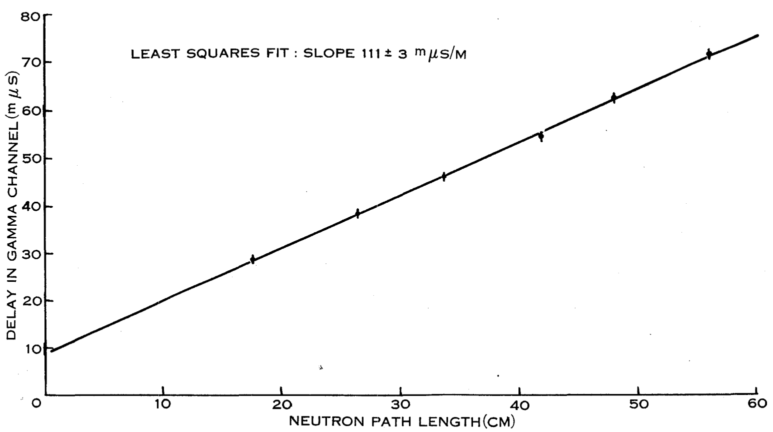

Fig. 4.—Delay v. flight path measurement for neutron group to the 6·50 MeV state (neutron direction 90°; beam energy 650 keV).

hibitively small for a series of delay distributions of the type hitherto described. However, the neutron yield measurements of Paris and Endt (1954) indicate that at this energy the intensities of the groups in the 0° direction should be in

TABLE 1

RESULTS OF DELAY DISTRIBUTION MEASUREMENTS FOR THE SECOND AND FOURTH EXCITED STATES OF ^{11}C

Deuteron Energy (keV)	Neutron Counter Angle	Slope of Delay-Distance Curve (mμs m^{-1})	Q (MeV)	Energy of Level (MeV)
580	0°	44 ± 2	$2\cdot16\pm0\cdot27$	$4\cdot3\ \pm0\cdot3$
580	0°	104 ± 4	$-0\cdot08\pm0\cdot04$	$6\cdot55\pm0\cdot04$
580	90°	115 ± 5	$-0\cdot04\pm0\cdot04$	$6\cdot51\pm0\cdot04$
630	0°	98 ± 2	$-0\cdot07\pm0\cdot02$	$6\cdot54\pm0\cdot02$
630	90°	111 ± 3	$-0\cdot06\pm0\cdot03$	$6\cdot53\pm0\cdot03$
			Mean Value:	$6\cdot53\pm0\cdot02$

the ratio $6:1:0\cdot3$, the $2\cdot8$ MeV group being the strongest and the $4\cdot9$ MeV group the weakest. Thus, a set of delay distributions taken under these conditions can be interpreted as giving a reasonable value of the energy of the $4\cdot26$ MeV state only.

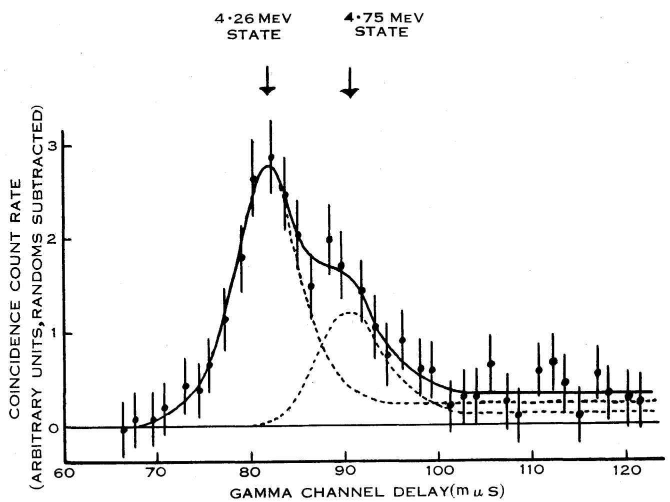

Fig. 5.—Delay distribution of neutrons to the $4\cdot26$ and $4\cdot75$ MeV states (neutron direction 90°; flight path $171\cdot5$ cm).

In this case, the discriminator setting in the neutron channel could be increased to remove noise pulses and also those due to the annihilation radiation of the ^{11}C. The resulting improvement in the true-to-random ratio and in resolution is evident in Figure 3. Table 1 includes the results of the single set of delay distributions made on this group.

(c) *The Neutron Group to the 4·75 MeV State of ^{11}C*

In the interpretation of the coincidence γ-ray spectra (Section IV (c)) it is desirable to have an estimate of the relative intensities of the neutron groups to the 4·26 and 4·75 MeV states. To provide such an estimate, a single delay distribution was taken over a flight path of 171·5 cm in the 90° direction. The angular distribution measurements of Graue (1956) indicate that in this direction the intensity of the weaker group (to the 4·75 MeV state) should be a maximum, while that of the stronger group should be at its minimum value. The result of this measurement (a 30-hr run), performed with a 260 $\mu g\ cm^{-2}$ target and a beam current of 0·5 μA at 600 keV bombarding energy, is shown in Figure 5. Comparison with the delay distribution shown in Figure 3 for the (effectively) monoenergetic neutron group of approximately the same energy shows the presence of two unresolved neutron groups. The separation of their two delay peaks is estimated to be 9 ± 2 mμs, corresponding to an energy difference of $0\cdot5\pm0\cdot1$ MeV, in agreement with other determinations of the energies of these two levels, and the ratio of their intensities is approximately 2, the group going to the second excited state being the more intense.

IV. Coincidence γ-Ray Spectra

(a) *Energy Calibration*

The spectra of the γ-rays in coincidence with the various neutron groups were recorded in a 100 channel pulse-height analyser (Sunvic type PHA2). Calibration points were obtained from the spectra of the 2·62 MeV γ-ray of ^{208}Pb (from a radiothorium source) and the 4·43 MeV γ-ray of ^{12}C (from a Po-Be source). With the beam striking the target the count rate in the γ-counter was very high, with large contributions from the ^{11}C (20-min half-life) annihilation radiation from the target and the neutron-induced ^{128}I (25-min half-life) activity in the NaI(Tl) crystal itself. This high count rate, estimated to be in excess of 10^5 per sec, had to be tolerated in order to obtain usable coincidence count rates. The resultant pile-up of pulses was sufficient to make the pulse-height resolution of the counter a good deal worse than could be obtained at low count rates, and also slightly reduced the gain of the photomultiplier. For this reason, calibration spectra were taken several times during each run, the beam being removed from the target only for the few minutes required to insert the radioactive sources and record the spectra, so that, under these conditions, the total count rate in the counter was still very high. Typical spectra are shown in Figure 6.

In addition, the energy of the ground state transition from the 6·50 MeV state could be regarded as being known from our delay distribution measurements to a better accuracy than we could hope to achieve in our scintillation spectra. Hence, in the coincidence spectra in which this γ-ray appeared, it provided a further calibration point, obtained during the actual running conditions for the coincidence spectrum. The fact that this point, together with the two obtained from radiothorium and Po-Be, gave a pulse-height versus energy relation which was linear within the experimental accuracy was regarded as a check on the validity of the calibration procedure using the radioactive sources described above.

(b) γ-Rays from the 4·26 MeV Level of ^{11}C

With the neutron counter in the 0° direction and a short flight path, the γ-rays in coincidence with the unresolved neutron groups to the 4·26 and 4·75 MeV states will be principally those due to de-excitation of the second excited state. A spectrum obtained using the small NaI(Tl) crystal is shown in Figure 7. Comparison of this figure with Figure 6 (*b*) clearly suggests the presence

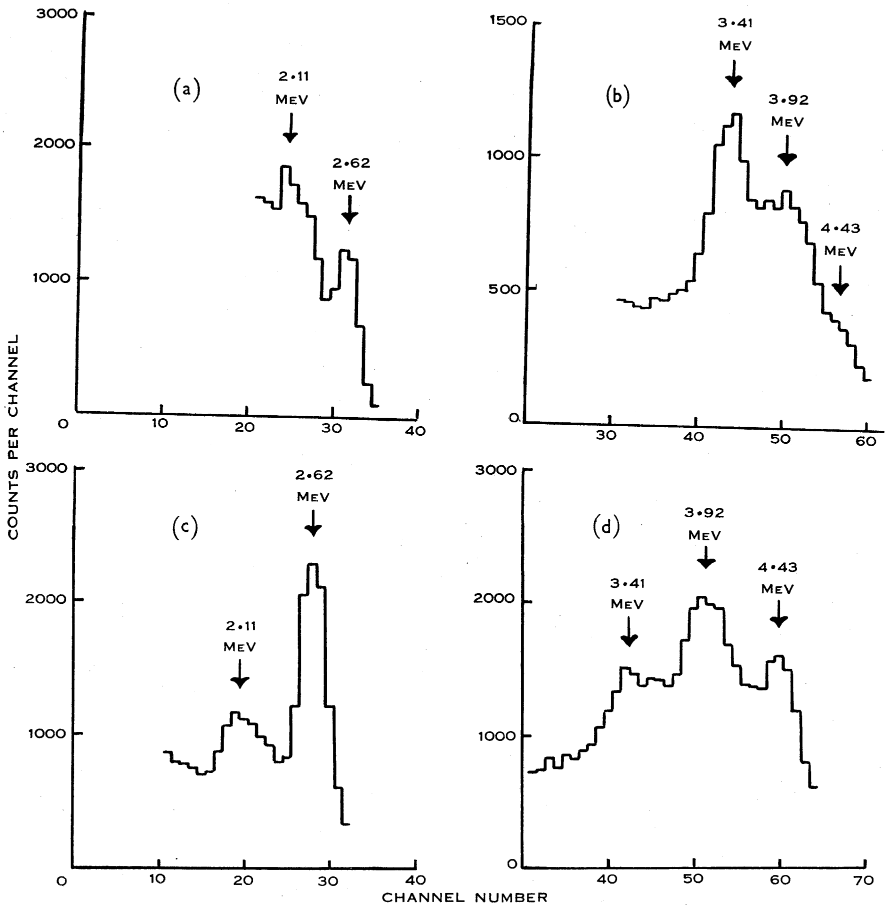

Fig. 6.—Calibration γ-ray spectra. (*a*) RdTh, $1\frac{1}{2}$ by 1 in. crystal, (*b*) Po-Be, $1\frac{1}{2}$ by 1 in. crystal, (*c*) RdTh, 3 by 3 in. crystal, (*d*) Po-Be, 3 by 3 in. crystal.

of only one γ-ray. The poorer resolution probably results from a combination of the higher count rate and small random drifts in gain during the run. For the runs reported here, no systematic drifts in the calibration spectra were observed, although random drifts of up to ± 1 channel did occur at times.

The main peak in Figure 7 is interpreted as the two-quantum escape peak of a γ-ray of energy $4\cdot 2 \pm 0\cdot 1$ MeV, and this is identified as the ground state transition from the 4·26 MeV state. A cascade from this level through the 2·01 MeV state would produce two γ-rays of energy in the vicinity of 2 MeV.

From Figure 7 we conclude that the intensity of any 2 MeV radiation which may be present is less than 10 per cent. of that of the 4·2 MeV γ-ray and hence the transition probability for de-excitation via the 2·01 MeV state is less than 5 per cent. of that for the ground state transition. However, it will be seen, in the following section, that this upper limit may be reduced to $2\frac{1}{2}$ per cent.

(c) γ-Rays from the 4·75 MeV State of ^{11}C

When the neutron counter is in the 90° position, our delay distribution measurements have shown that approximately one-third of the true coincidences in the composite delay peak of the neutron groups to the 4·26 and 4·75 MeV

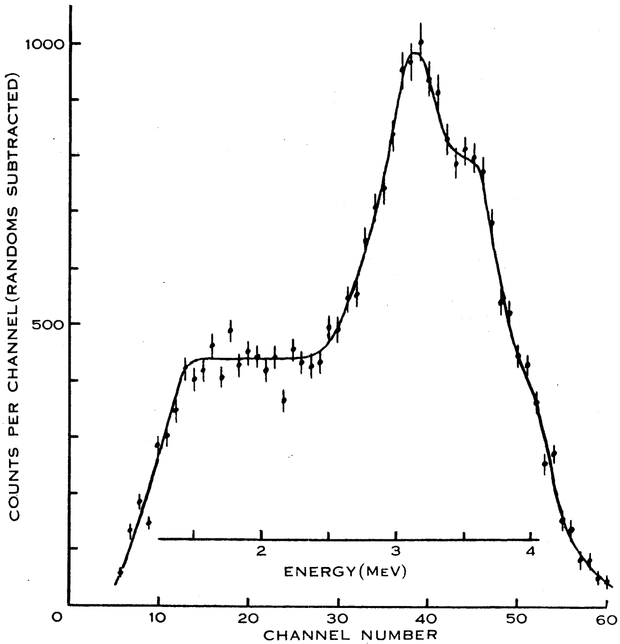

Fig. 7.—γ-Ray spectrum from 4·26 MeV state (small NaI(Tl) crystal).

states are associated with the 4·75 MeV state. Thus the γ-ray spectrum in coincidence with this composite delay peak may provide some information about the de-excitation of this level.

With a short flight path and using the small NaI(Tl) crystal the spectrum shown in Figure 8 was obtained. It is not possible to select either of the two curves shown in this figure as being a better fit to the experimental points than the other and it is clear that very good statistics indeed would be needed to be able to decide between them. Thus, from this measurement we are not able to discover whether or not the 4·75 MeV state is de-excited to any extent by a ground state transition.

A spectrum taken under the same conditions but using the large NaI(Tl) crystal is shown in Figure 9. The " smearing out " of the spectrum from a crystal of this size by the use of a high count rate is clearly seen by reference to

Figure 6 (*d*). It is also apparent from Figure 7 that this effect is less serious in the spectrum from the small crystal, partly due to the lower count rate and partly due to the nature of the latter spectrum in which the two-quantum escape peak is dominant at these energies.

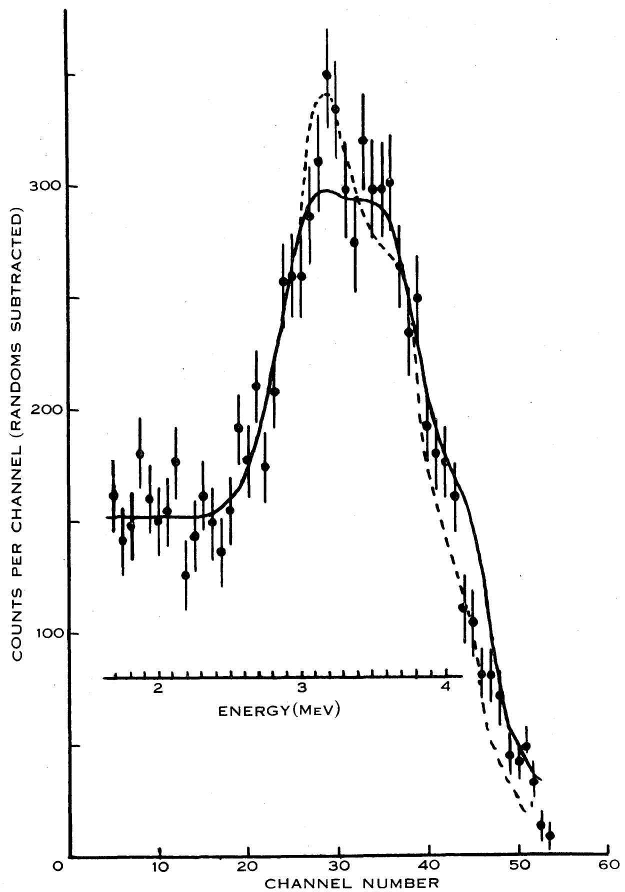

Fig. 8.—γ-Ray spectrum from 4·26 and 4·75 MeV states (small NaI(Tl) crystal). The full curve is the spectrum expected if one-third of the γ-rays were 4·75 MeV and two-thirds 4·26 MeV. The dotted curve is the spectrum for 4·26 MeV alone.

Figure 9 again provides no evidence for or against the presence of a 4·8 MeV γ-ray but does confirm the low intensity of any cascade through the 2·01 MeV state. One could perhaps suggest the presence of a peak having a height of the order of 5 per cent. of that of the main peak in the vicinity of 2 MeV, as shown by the dotted curve in Figure 9, but it would hardly be justified by the statistics of the points in this region. Thus it seems reasonable to set the upper limit for de-excitation of the 4·26 and 4·75 MeV states combined via the 2·01 MeV state as $2\frac{1}{2}$ per cent. of the total probability of de-excitation of these levels either by direct ground state transitions or by cascade from the 4·75 MeV to the 4·26 MeV state and thence to the ground state. Hence less than about $7\frac{1}{2}$ per cent. of the transitions from the 4·75 MeV excited state alone are from this level direct to the first excited state. However, the measurements provide no information

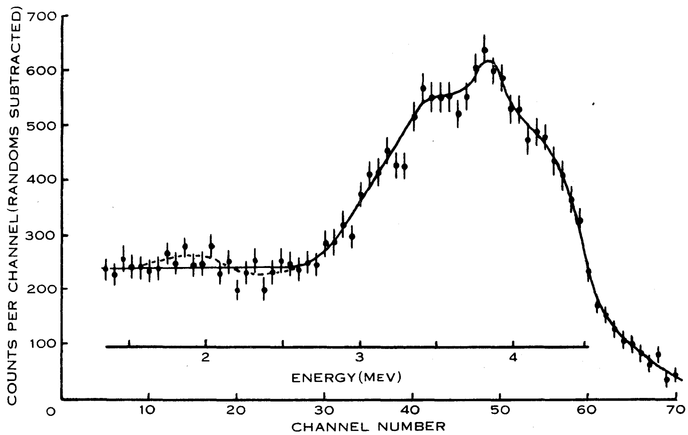

Fig. 9.—γ-Ray spectrum from 4·26 and 4·75 MeV states (large NaI(Tl) crystal).

about the probability of a cascade from the 4·75 MeV to the 4·26 MeV state. It was not possible to obtain any observations of neutrons in coincidence with a 0·5-MeV γ-ray (the first transition in such a cascade) because of the high annihilation radiation background.

TABLE 2

PEAKS IN THE SPECTRA OF γ-RAYS IN COINCIDENCE WITH THE NEUTRON GROUP TO THE FOURTH EXCITED STATE OF ^{11}C (SMALL NaI(Tl) CRYSTAL MEASUREMENTS)

Peak Energy (MeV)			Identification
Run 1	Run 2	Mean	
*	1·7 (?)		
*	$2\cdot3\pm0\cdot1$	2·3	2·3 MeV ; full energy peak
$3\cdot2\pm0\cdot1$	$3\cdot4\pm0\cdot1$	3·3	4·3 MeV ; double escape peak
$3\cdot7\pm0\cdot1$	$3\cdot9\pm0\cdot1$	3·8	{ 4·3 MeV ; single escape peak 4·8 MeV ; double escape peak
$4\cdot3\pm0\cdot2$	$4\cdot3\pm0\cdot15$	4·3	4·8 MeV ; single escape peak†
6·50	6·50		6·50 MeV ; double escape peak (calibration point)

* Spectrum unreliable in this region due to electronic fault.

† Plus a small contribution from the 4·3 MeV full energy peak.

(d) γ-*Rays from the 6·50-MeV State*

The spectrum of γ-rays in coincidence with the low energy neutron group was observed with both the small and large NaI(Tl) crystals. The small crystal results are shown in Table 2, and one of the small crystal spectra is shown in

Figure 10. It will be seen that there is clear evidence for a cascade of two γ-rays of approximate energies $2 \cdot 3$ and $4 \cdot 3$ MeV. Using the best available level energies as shown in Figure 1, the two possible cascades which might fit this description are

(i) $4 \cdot 49$ MeV followed by $2 \cdot 01$ MeV, through the first excited state, and

(ii) $2 \cdot 24$ MeV followed by $4 \cdot 26$ MeV, through the second excited state.

We believe that the accuracy of our γ-ray measurements is sufficient to exclude the first of these possibilities. The peak falling at $2 \cdot 3$ MeV in Figure 10 is well defined and appears at the same energy in the coincidence spectrum obtained with the large NaI(Tl) crystal (Fig. 11). Our energy calibration seems

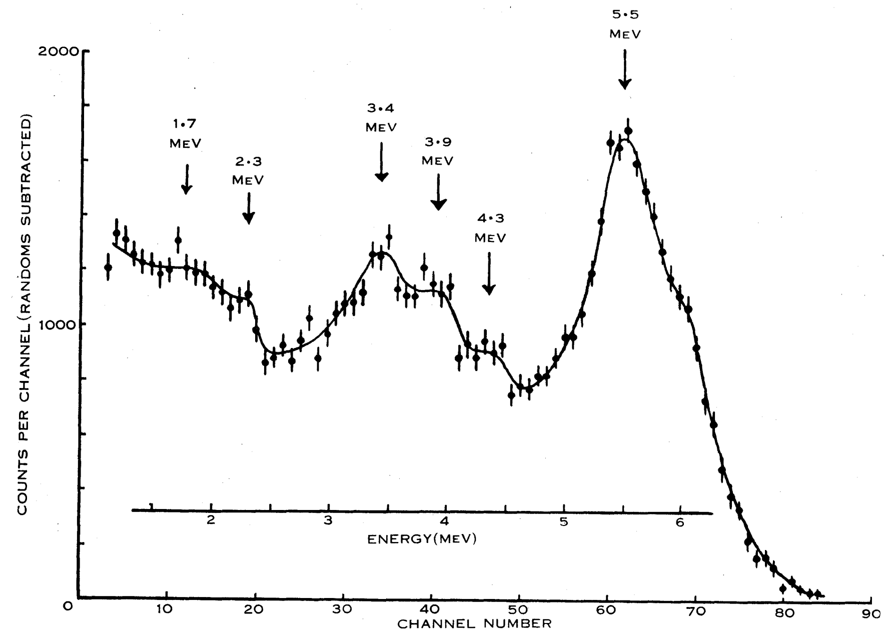

Fig. 10.—γ-Ray spectrum from $6 \cdot 50$ MeV state (small NaI(Tl) crystal).

reliable enough to exclude the possibility that this peak could be due to a $2 \cdot 0$ MeV γ-ray. In the same way, the peaks in the middle energy range cannot be fitted to a $4 \cdot 5$ MeV γ-ray, particularly in view of the proximity of our $4 \cdot 43$ MeV calibration points. Thus it seems that the predominating cascade from the fourth excited state is via the second excited state, and that the probability of occurrence of this cascade is somewhat less than, but of the same order of magnitude as that of the direct ground state transition.

There is also evidence, more particularly from the small crystal spectra, for the presence of a $4 \cdot 8$ MeV γ-ray, corresponding to the $4 \cdot 75$ MeV ground state transition from the third excited state. The main evidence for this is the presence of the peak at $4 \cdot 3$ MeV which is identified as the one-quantum escape peak of a $4 \cdot 8$ MeV γ-ray. Comparison with Figure 7 indicates that a $4 \cdot 3$ MeV γ-ray would not produce such a full energy peak. The lack of structure in the 3–5 MeV region of the large crystal spectrum precludes any definite identification of a 4·8 MeV γ-ray in this case. There is some evidence in both the small and large crystal spectra for the presence of a 1·75 MeV γ-ray which must precede the 4·75 MeV transition. However, the spectra in this region cannot be regarded as very reliable since, in order to obtain pulses of this magnitude, the necessary

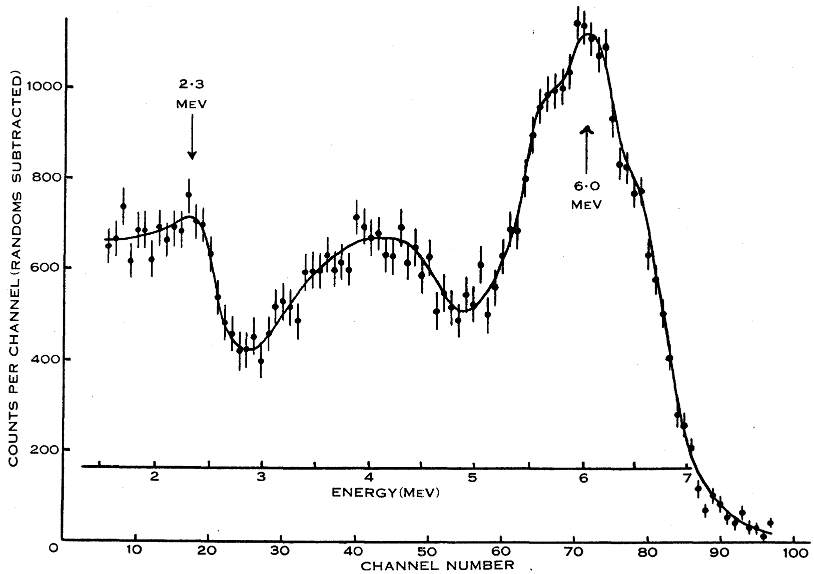

Fig. 11.—γ-Ray spectrum from 6·50 MeV state (large NaI(Tl) crystal).

discriminator setting in the γ-channel was low enough to admit a large number of background pulses from the ^{128}I activity in the crystal. Hence the absence of a sharp peak at 1·75 MeV cannot be taken as definite evidence against the presence of a 1·75 MeV γ-ray.

From these coincidence γ-ray spectra we conclude that the principal γ-ray transitions between the low-lying levels of ^{11}C are those shown in Figure 12 below.

V. Discussion

(*a*) *Energies of Excited States of* ^{11}C

Our time-of-flight measurement of the energy of neutrons to the 6·50 MeV state of ^{11}C is our most precise estimate of the excitation energy of an ^{11}C level. Our value of 6·53 ± 0·02 MeV is in agreement with the values of 6·50 ± 0·03 MeV found by Bent *et al.* (1955), and 6·52 ± 0·05 MeV by Sample *et al.* (1955), from γ-ray energy measurements, but is not in agreement with the value of 6·40 ± 0·04 MeV found by both Johnson (1952) and Cerineo (1956) from measurements of the energy of this same neutron group, using photographic plates, nor with the value of 6·476 ± 0·020 MeV found by Neilson, Dawson, and Johnson (1959), also using a time-of-flight technique, although the disagreement, in this case, is not large. The accuracy of our determination depends only on the accuracy of measurement of the neutron flight path and of calibration of the variable delay. Flight paths could be readily measured to better than 0·5 per cent. and the variable delay was known at all settings to within 0·5 mμs, by comparison with the period of a BC221 oscillator. We have been unable to detect any systematic error in our measurements to account for these discrepancies between our result and those of other workers.

The other estimates of excitation energies from our results are the value of $4\cdot2\pm0\cdot1$ MeV for the 4·26 MeV state, from a γ-ray measurement, and an energy difference of $0\cdot50\pm0\cdot05$ MeV between the 4·26 and 4·75 MeV states from a delay distribution of neutrons. Both of these values are in agreement with those given by Ajzenberg-Selove and Lauritsen (1959), but are not sufficiently precise to influence their values in any way.

(b) γ-*Rays*

Since the transition probabilities for the γ-rays observed are not among those calculated by Kurath (1957) on the intermediate coupling model, we have been tempted to apply the cruder estimates of Weisskopf (1951) to find the most probable multipolarities of the observed transitions. In doing this we have been encouraged by the work of Lane and Radicati (1954) on A=13 nuclei, which showed that the intermediate coupling and experimental values of the transition probabilities differed from the Weisskopf estimates by a factor of only about 10. Table 3 lists the Weisskopf transition probabilities of interest.

TABLE 3

WEISSKOPF ESTIMATES FOR TRANSITION PROBABILITIES IN ^{11}C

E (MeV)	T ($M1$) (sec^{-1})	T ($E2$) (sec^{-1})	T ($M3$) (sec^{-1})
0·5	5×10^{12}	10^{8}	4
1·75	2×10^{14}	6×10^{10}	3×10^{4}
2·25	4×10^{14}	2×10^{11}	2×10^{5}
2·74	7×10^{14}	6×10^{11}	6×10^{5}
4·26	3×10^{15}	5×10^{12}	10^{7}
4·75	4×10^{15}	9×10^{12}	3×10^{7}
6·50	10^{16}	5×10^{13}	3×10^{8}

Since the $l_p=1$ stripping patterns fix the parities of the ground and first four excited states of ^{11}C as odd, the only possible multipole transitions to be observed between these levels are $M1$, $E2$, and $M3$. $E4$ and higher order multipoles have mean lives too long to be observed by our technique.

The comparable intensities of the 6·5 MeV and 1·75 or 2·25 MeV γ-rays in the decay of the 6·50 MeV state is readily accountable if, and only if, the 6·5 MeV transition is $E2$ and the lower energy transition $M1$, particularly since at least some $E2$ enhancement is to be expected. Now in Section I it was pointed out that the most likely value of the ground state spin is 3/2 ; this value will be assumed throughout the following discussion. In this case the spin of the

$6 \cdot 50$ MeV state would be $7/2^-$ which is the assignment given by Ferguson *et al.* (1958) to the corresponding level in ^{11}B. The possibility that the $6 \cdot 5$ MeV γ-ray is $M1$ or $M3$ is very remote in view of the comparable intensity of the lower energy component.

The existence of the $2 \cdot 3$ and $4 \cdot 8$ MeV γ-rays in this decay scheme would indicate that both the $1 \cdot 75$ and $2 \cdot 25$ MeV transitions occur, and, since both would have to be $M1$ to compete with the $6 \cdot 5$ MeV $E2$ transition, the spins of the $4 \cdot 75$ and $4 \cdot 26$ MeV states would be restricted to 5/2, 7/2, or 9/2. Also, if both the $4 \cdot 75$ and $4 \cdot 26$ MeV ground state transitions are observed they cannot be $M3$, since this would correspond to a mean life of about 50 mμs which would

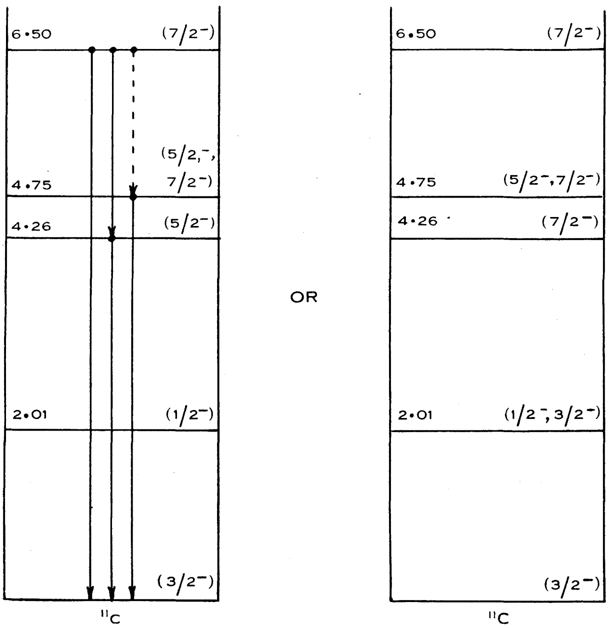

Fig. 12.—Spin assignments for low excited states of ^{11}C.

have shown up as a considerable distortion of the delay peaks. This would then eliminate 9/2 as a possible spin for either the $4 \cdot 75$ or $4 \cdot 26$ MeV levels. While the presence of the $4 \cdot 26$ MeV γ-ray is certain, so that for this case these conclusions are valid, the evidence for the $4 \cdot 75$ MeV γ-ray is certainly less strong. However, it should be noted that the absence of this γ-ray would not affect the argument as to the spin of any level other than that at $4 \cdot 75$ MeV.

The absence of any evidence in the decay scheme of the $6 \cdot 50$ MeV level for a cascade through the $2 \cdot 01$ MeV level suggests that this transition, if it occurs, is not $M1$, and consequently that the spin of the $2 \cdot 01$ MeV level is not 5/2, 7/2, or 9/2. However, the expected intensity for $E2$ or $M3$ is so low that neither of these would be observed, and so spin values of 1/2 or 3/2 are possible. If the spin of this level is 3/2 then the $4 \cdot 26$ MeV and possible $2 \cdot 25$ MeV transitions in the decay of the $4 \cdot 26$ MeV state would be both $M1$ or both $E2$. Since an upper limit of $2\frac{1}{2}$ per cent. is placed on the intensity of the $2 \cdot 25$ MeV component relative to the $4 \cdot 26$ MeV component, and the theoretical relative intensities for $M1$ and $E2$ transitions are 1/10 and 1/20 respectively, it is unlikely that both are $M1$, but both $E2$ is possible ; i.e. if the $2 \cdot 01$ MeV state is $3/2^-$, then the $4 \cdot 26$ MeV state would be $7/2^-$. However, if the $2 \cdot 01$ MeV state is $1/2^-$ then the $4 \cdot 26$ MeV state could be $5/2^-$ or $7/2^-$, the unobserved $2 \cdot 25$ MeV transition being of higher multipole order than the $4 \cdot 26$ MeV transition in either case. Thus a spin of $7/2^-$ for the $4 \cdot 26$ MeV state may be associated with $1/2^-$ or $3/2^-$ for the $2 \cdot 01$ MeV state, while $5/2^-$ for the $4 \cdot 26$ MeV state is associated with only $1/2^-$ for the $2 \cdot 01$ MeV state. All these spin conclusions are summarized in Figure 12, in which are also shown the γ-ray transitions observed (firm lines) and inferred (dotted line).

In conclusion, it is interesting to note the extent to which the spin values found here for ^{11}C agree with those found for ^{11}B and those predicted by the intermediate coupling model. The assignment of $1/2^-$ for the first excited state in ^{11}B seems fairly definite, while $5/2^-$ and $7/2^-$ for the second and fourth excited states respectively are found by Ferguson *et al.* (1958). Our results are in complete agreement with these assignments, but in the third excited state there is an anomaly. Ferguson *et al.* (1958) have observed a 12 per cent. decay of the third excited state through the first, from which they conclude spin $3/2^-$ for the third state. However, Wilkinson and Alburger (1959) are unable to reconcile a spin value of less than $5/2^-$ for this level with their measurements on the β decay of ^{11}Be. Our results for ^{11}C make a spin of $3/2^-$ for the third excited state of ^{11}C seem unlikely also. The intermediate coupling model requires spins of $5/2^-$ and $7/2^-$ for the second and third excited states (or vice versa), and whilst Wilkinson and Alburger's results for ^{11}B and also our results for ^{11}C are in accord with this requirement, it has not yet been shown whether the model is capable of predicting the $E2$ enhancement necessary to account for the cascade through the first excited state observed by Ferguson *et al.*

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