PHYSICAL REVIEW VOLUME 119, NUMBER 6 SEPTEMBER 15, 1960

Reaction $C^{14}(p,n)N^{14}$

J. K. BAIR, R. D. EDGE,* AND H. B. WILLARD
Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Received April 25, 1960)

The reaction $C^{14}(p,n)N^{14}$ has been studied up to 5-Mev bombarding proton energy with good resolution using targets of high isotopic enrichment. Levels previously unseen in this reaction were found at proton energies of 3.19 Mev ($\Gamma=6$ kev), 3.38 Mev ($\Gamma=24$ kev), 3.63 Mev ($\Gamma=13$ kev), 3.89 Mev ($\Gamma=35$ kev), 4.19 Mev ($\Gamma=112$ kev), 4.24 Mev ($\Gamma=27$ kev), 4.61 Mev ($\Gamma=140$ kev), and 4.93 Mev ($\Gamma=106$ kev). Excitation curves at three angles in the region of 2.9-Mev proton energy show the effect of the previously known $J=\frac{3}{2}^-$ ($\Gamma=80$ kev) resonance interfering with a level of opposite parity. Effects of the nearby $J=\frac{7}{2}^-$ ($\Gamma=40$ kev) level are not seen, presumably due to the low penetrability of the outgoing F-wave neutron. The thresholds for the second and third neutron groups were investigated using a lithium iodide detector. A new threshold, that for production of the third neutron group, was measured to be 4.910 ± 0.008 Mev in agreement with the known energy of the second excited state in N^{14}.

INTRODUCTION

AJZENBERG-SELOVE and Lauritsen[1] have recently reviewed the status of the energy levels in N^{15}. The reaction C^{14} plus protons has been used by several groups (see reference 1 for detailed bibliography); however, the yield of neutrons has previously been published only below about 3.5 Mev. Unpublished data obtained at this laboratory using an undesirably thick C^{14} target of low isotopic concentration extended the 0° and 90° yields of the reaction $C^{14}(p,n)N^{14}$ to above 5-Mev bombarding energy. When a quantity of barium carbonate having an enrichment of about 75% C^{14} recently became available, the neutron yield was rerun with improved resolution.

EXPERIMENTAL PROCEDURE

C^{14} targets were prepared[2] by using the barium carbonate to produce acetylene,[3] and then depositing the carbon in an electrical discharge between two platinum blanks placed in a low-pressure acetylene atmosphere.[4] The actual composition of the target layer is unknown, although the weight of the layer was determined to be roughly 40 micrograms per cm^2. In order to reduce ordinary carbon deposition, the proton beam from the 5.5-Mv Van de Graaff was run through a liquid nitrogen cold trap adjacent to the target. Two targets (made at the same time) were used in the course of the investigation and gave essentially identical results. This work followed an extensive energy recalibration of the accelerator, and it is felt that the machine energy is known to $\pm0.1\%$ relative to the $Li^7(p,n)Be^7$ threshold. Neutron detectors used consisted of conventional "long" counters, propane recoil counters, and a lithium iodide crystal. The latter was used as a neutron spectrometer in some energy regions.

EXPERIMENTAL RESULTS

Figure 1 shows our original yield curves for neutrons as measured at laboratory angles of 0° and 90° with respect to the incoming protons. The detector used was a conventional "long counter." These older measurements were made using an undesirably thick target of low C^{14} enrichment. In the energy region below 3.5 Mev, where these data overlap those of other investigators, the agreement is quite satisfactory. The resonances agree in location and width and the threshold for production of neutrons leaving the residual N^{14} nucleus in its first excited state is evident at 3.152 ± 0.005 Mev proton bombarding energy in the laboratory system. This is in excellent agreement with Sanders' value[5] of 3.1496 ± 0.0011 Mev and with the accepted energy of 2.312 ± 0.0012 Mev for the first excited state in N^{14}. Agreement with the level structure obtained from the reaction $B^{11}+\alpha$ was not very good, however. In particular, our results did not show the narrow (<3 kev) level at an energy of excitation of 13.15 Mev, the 6-kev level at 13.18 Mev, nor the level at 13.36-Mev excitation, although there was some possible indication of the latter on the low-energy side of the large peak at a proton energy of 3.41 Mev. In addition, the peak at about 2.9-Mev proton energy had been found to be a pair of closely spaced, rather wide levels in the $B^{11}+\alpha$ work.[6] Mainly for these reasons, the neutron yield curves were rerun with the thinner, high activity C^{14} targets.

Figure 2 shows the results of these new measurements from about 3.1 Mev to 5 Mev. The bottom curve is the yield at 90° and the next curve is the yield at 0°, both as measured with long counters at about 50 cm from the target; the second curve from the top is the 141°

* Summer Research participant from the University of South Carolina, Columbia, South Carolina.
[1] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. 11, 1 (1959).
[2] We are greatly indebted to B. J. Massey and J. C. Smith of the Oak Ridge National Laboratory, Isotopes Division, for the preparation of the C^{14} targets.
[3] S. Monat, C. Robbins, and A. R. Ronzio, Atomic Energy Commission Report AECU-672 (unpublished).
[4] R. A. Douglas, B. R. Gasten, and A. Mukerji, Can. J. Phys. 34, 1097 (1956).
[5] Richard M. Sanders, Phys. Rev. 104, 1434 (1956).
[6] L. L. Lee, Jr., and J. P. Schiffer, Bull. Am. Phys. Soc. 3, 188 (1958), and Phys. Rev. 115, 160 (1959).

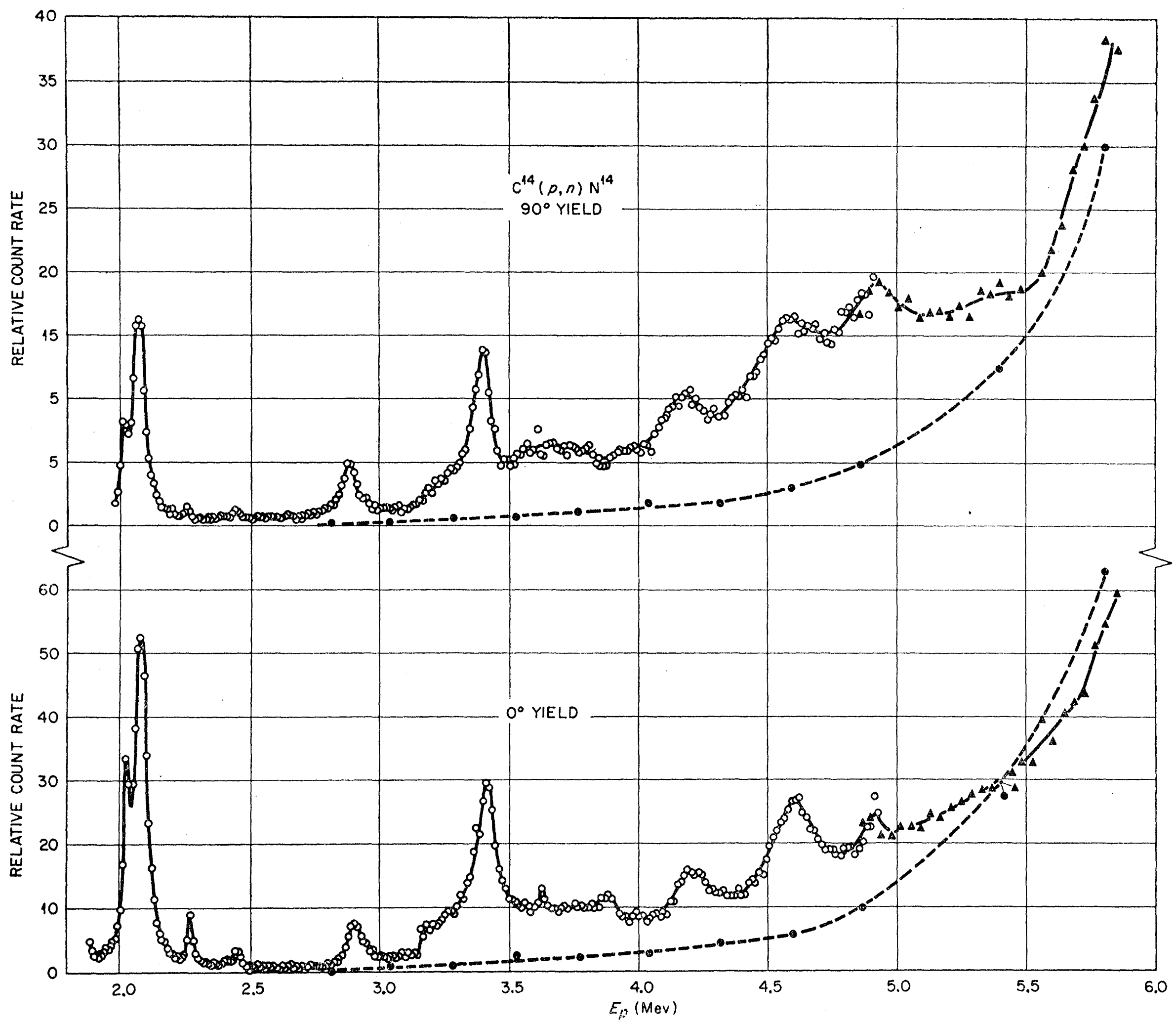

FIG. 1. The original yield curve of neutrons from $C^{14}(p,n)N^{14}$ at laboratory angles of 0° and 90° as a function of bombarding proton energy. These data were taken with fairly thick targets of low isotopic content. The dotted curve indicates background.

yield as measured with a long counter at about 70 cm from the target, and the top curve is the 0° yield as measured by a propane recoil counter. All three curves at 0° and 90° were taken simultaneously, but the 141° curve was taken at a later date. All long counter data are normalized to the same sensitivity. Angles and energies are in the laboratory system and yields are uncorrected for laboratory to center-of-mass solid angle conversion. We do not see the very narrow resonance which might be expected to fall just below the threshold for the second group of neutrons. Just above the threshold the 6-kev resonance appears in the 0° and 141° yield and is also apparent in both the long counter data and the recoil counter data. The recoil counter was not sensitive to the neutrons of the second group. The resonance expected on the low-energy side of the 3.42-Mev resonance is clearly evident in both sets of 0° data. In addition, our more recent results suggest that the resonance structure appearing in our original data at 4.20-Mev bombarding energy may represent two levels. Table I summarizes these data.

It is interesting to note the sharp break superimposed on the wide 4.93-Mev resonance in the 0° long counter data. This break does not occur in the data at other angles, nor does it occur in the 0° recoil counter data. It is assigned to the threshold for production of the third group of neutrons leaving the residual N^{14} in its second excited state. Figure 3 shows another set of data covering this threshold region. The sharp rise occurs at 4.910±0.008 Mev which gives an energy of 3.952±0.008 Mev for the second excited state in N^{14}. This is to be compared with the previously accepted value of 3.945±0.005 Mev.

Figure 4 shows the neutron yield in the vicinity of 2.9-Mev proton energy. These data were obtained with the long counter at approximately 60 cm from the

TABLE I. Comparison of the level structure of N^{15} as seen by the various reactions leading to excitation energies between approximately 12 and 15 Mev. Columns 1 through 6 give the proton bombarding energies, experimental width, and energy of excitation in the N^{15} compound nucleus as determined from the work reported in this paper. Columns 7, 8 and 9 give information previously reported by other investigators. Columns 10 and 11 give the widths and excitation energies as determined by the bombardment of B^{11} with alpha particles. The last two columns tabulate these quantities as determined by the $N^{14}+n$ reaction. (Note that the 14.51-Mev level as seen by the $B^{11}+\alpha$ reaction is taken from the curve of Bonner *et al.*[a] but it not listed by the authors.)

Our new $C^{14}(p,n)$			Our original $C^{14}(p,n)$			$C^{14}+p$			$B^{11}+\alpha$		$N^{14}+n$	
E_p (Mev)	Γ (kev)	E_{ex} (Mev)	E_p (Mev)	Γ (kev)	E_{ex} (Mev)	E_p (Mev)	Γ (kev)	E_{ex} (Mev)	Γ (kev)	E_{ex} (Mev)	Γ (kev)	E_{ex} (Mev)
			2.02	20	12.10	2.025	18	12.104		12.10	22	12.102
			2.08	60	12.15	2.079	53	12.154		12.15	54	12.150
			2.27	20	12.33	2.272	22	12.335			22	12.331
			2.45	50	12.50	2.450	34±4	12.501	66	12.50	24	12.503
2.90	80	12.92	2.89	80	12.91	2.908	71±5	12.928	80	12.92	...	12.94
...	...	...	...	...	...				40	12.93		
...	...	...	...	...					<3	13.15		
3.19	6	13.19	...	...					8	13.18		
3.38	24	13.37	...	...					29	13.36		13.34
...	...	...	...	...	...				40	13.41		
3.42	66	13.41	3.41	80	13.40							13.59
3.63	13	13.61	3.63	25	13.60				20	13.61		
									40	13.71		
3.89	35	13.85	3.88	50	13.84				70	13.85		13.82
									~10	14.08		
4.19	112	14.12	4.20	100	14.13							14.15
4.24	27	14.17							35	14.17		
4.61	140	14.51	4.60	150	14.51				150	14.51		
									72	14.63		
4.93	106	14.82	4.92	100	14.81				...	14.90		

[a] See reference 8.

target. They have been corrected for counter sensitivity and for the laboratory to center-of-mass conversion so as to give the yield in the center-of-mass system at the center-of-mass angles noted on the individual curves.

Spectra of the neutrons were taken at zero degrees by means of a small Li^6 iodide scintillation counter. Figure 5

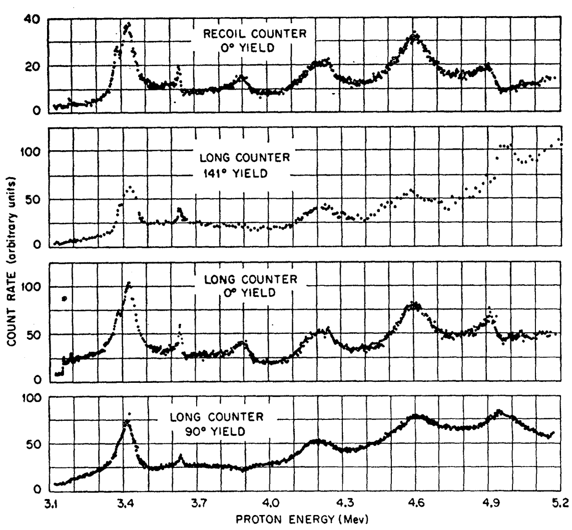

FIG. 2. The yield of neutrons from $C^{14}(p,n)N^{14}$. These data were taken with thin targets of high C^{14} content. The top curve is the 0° yield as measured by a propane recoil counter. The second curve from the top is the yield as measured with a long counter at 141° and about 70 cm from the target. The third curve and the bottom curve give, respectively, the 0° and 90° yield as measured by the long counter at about 50 cm from the target. The 0° and 90° curves were taken simultaneously. All long counter data are normalized to the same sensitivity.

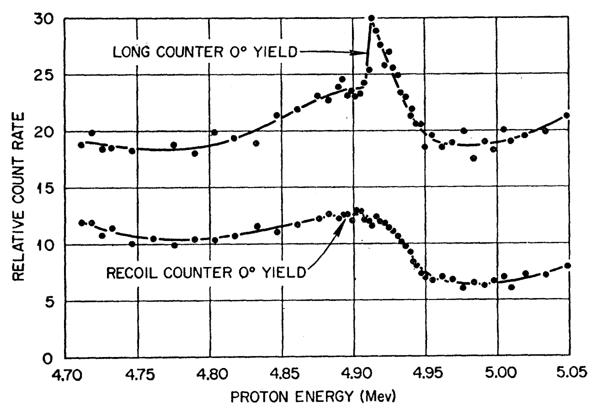

FIG. 3. The yield of neutrons at 0° covering the region of the threshold for the production of neutrons leaving the residual N^{14} nucleus in its second excited state.

shows two such spectra obtained just below and just above the threshold for the second neutron group. The peak at channel number 36 corresponds to pulses produced by low-energy neutrons, whereas the broad maximum at channel 55 corresponds to pulses caused by the main neutron group. It is quite evident that the data are consistent with the identification of the 3.152-Mev anomaly as a neutron threshold. Figure 6 shows the result of a similar experiment for the third group of neutrons, the pulse spectrum obtained just below the threshold being subtracted from that just above (note that the gain is not the same as it was for the data of Fig. 5). The large increase in low-energy neutrons at channel 42 again indicates that a threshold has been reached.

It had been hoped that, by taking lithium iodide spectra on and between the various resonances, branching ratios could be assigned. However, the resolution for the fast neutron groups was so poor as to make any sort of precise analysis impossible. An attempt was made to determine the second group neutron yield at 0° in the region between the threshold and 3.5-Mev proton energy by taking spectra at several proton energies, correcting the low-energy peak for the presence of the

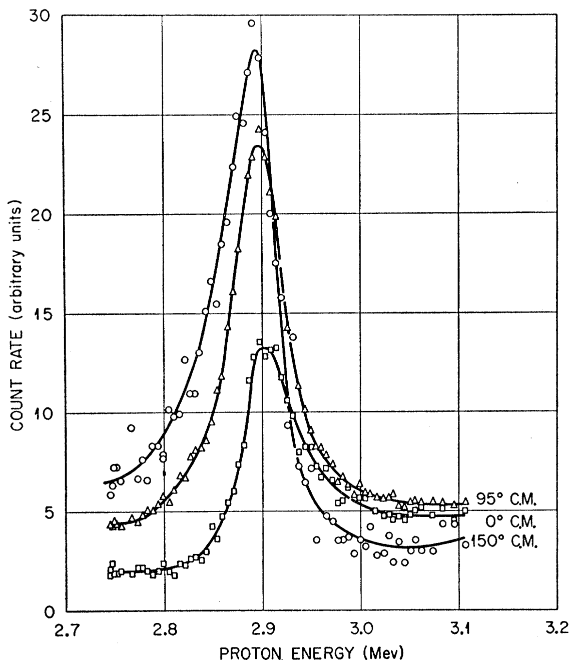

FIG. 4. The yield of neutrons in the vicinity of the doublet found by Lee and Schiffer (reference 6) in the $B^{11}(\alpha,p)C^{14}$ reaction.

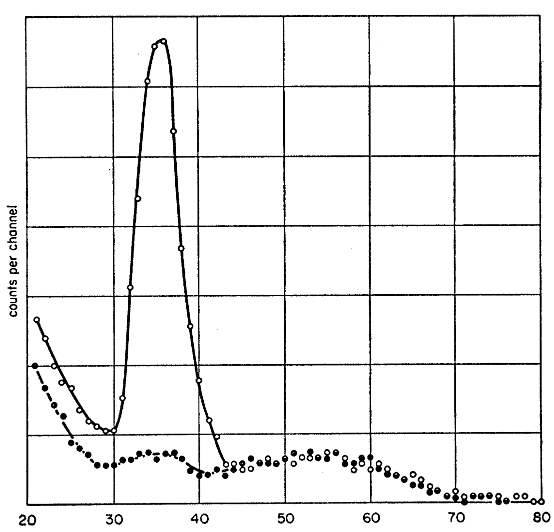

FIG. 5. The lithium iodide spectra of the neutrons just below and just above the threshold for the production of neutrons leaving the residual N^{14} nucleus in its first excited state.

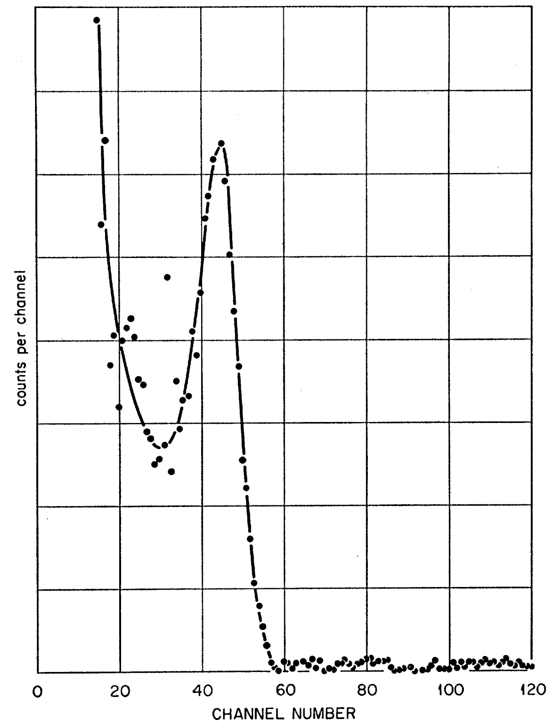

FIG. 6. The lithium iodide difference spectrum just below and above the threshold for the production of neutrons leaving the residual N^{14} nucleus in its second excited state.

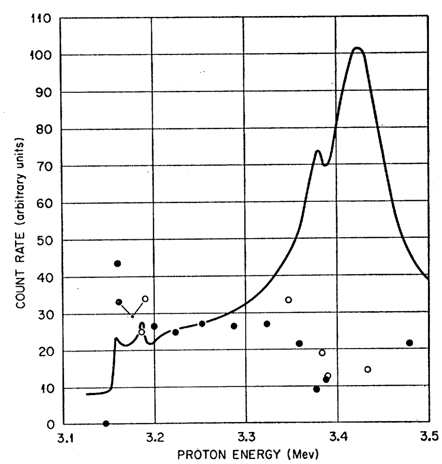

FIG. 7. The solid curve is the neutron yield as measured by the 0° long counter and is shown for reference purposes. The solid and open circles are two sets of 0° lithium iodide detector data (normalized at 3.175 Mev). The lithium iodide data represent the low-energy group corrected for the presence of the high-energy group and for the variation of the $Li^6(n,\alpha)T^3$ cross section with neutron energy.

high-energy neutrons and for the variation of the $Li^6(n,\alpha)T^3$ cross section with neutron energy. These data are shown in Fig. 7. Despite their rather limited accuracy, the data do indicate the presence of a very broad level just at or above the threshold.

Figure 8 shows the N^{14} neutron total cross section in the region of excitation of interest here. These data were

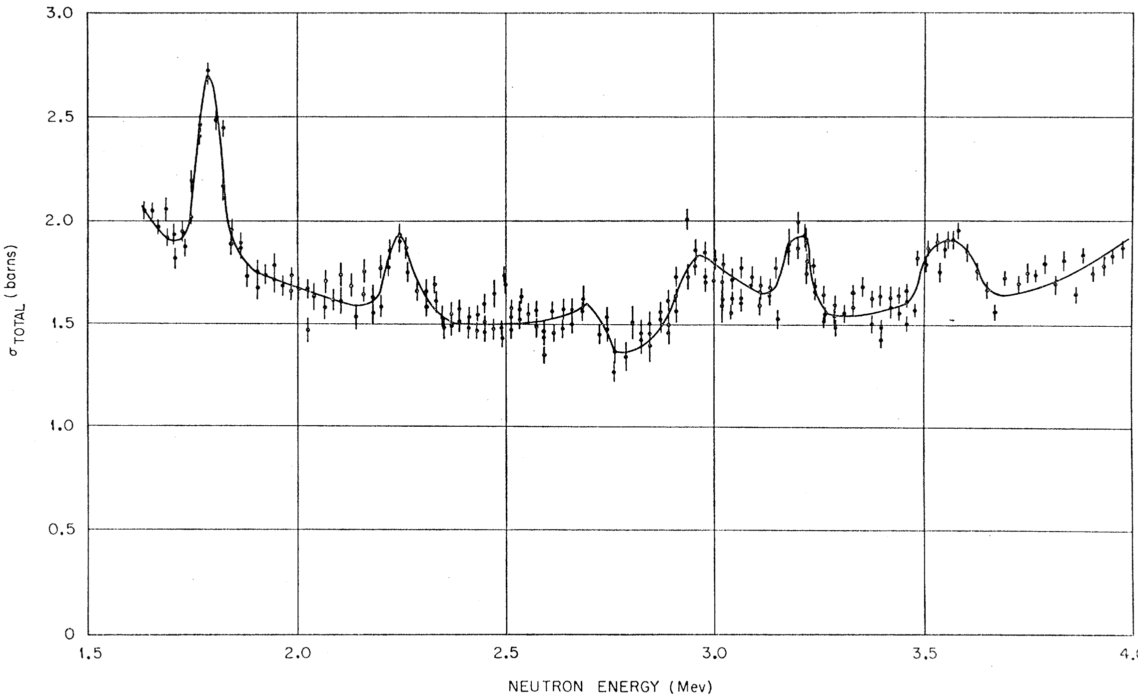

FIG. 8. The total neutron cross section of N^{14}. The resolution of these previously unpublished data is about 35 kev. Details can be found in reference 7.

obtained at this laboratory several years ago,[7] but have not previously been published. Within the rather poor energy resolution used, these data are in fair agreement with the other reactions.

DISCUSSION

It is interesting to speculate as to why the threshold due to the first excited state is so pronounced in the $C^{14}+p$ reaction and yet has not been observed in the $B^{11}+\alpha$ reaction. Bonner *et al.*[8] find a narrow resonance quite close to the energy of the expected threshold, but this anomaly appears in both their 0°–20° and in their 70°–110° data and hence could not be the threshold. The most obvious explanation is that the $B^{11}+\alpha$ reaction can form only compound states of $T=\frac{1}{2}$, whereas $C^{14}+p$ can excite $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states, both of which are then able to decay to the first excited state in nitrogen. If the level responsible for most of the cross section at threshold is $T=\frac{3}{2}$, it would then be more likely to be seen in our reaction. The broad level at or just above threshold may be just such a level. The $B^{11}(\alpha,p)$ reaction has the same isotopic spin restrictions as the $B^{11}(\alpha,n)$, so any level which appears in either the (α,n) or (α,p) reaction would not be expected to be the $T=\frac{3}{2}$ level associated with the threshold.

Table I shows that all the resonances between excitations of 12.5 and 13.6 Mev appear in both the $C^{14}+p$ and $B^{11}+\alpha$ reactions with the possible exception of the one at 13.41 Mev which may be an energy degenerate pair; the resonance seen in the (α,p) reaction has a width of 30 or 40 kev, whereas the one seen in the $C^{14}+p$ reaction has a width of about 66 kev. It is possible that the former is a $T=\frac{1}{2}$ and the latter the $T=\frac{3}{2}$ level responsible for the threshold.

Lee and Schiffer,[6] from angular distributions of the $B^{11}(\alpha,p)C^{14}$ reaction, have determined that the anomaly observed by them at an energy of excitation of about 12.92 Mev in N^{15} is due to two very closely spaced ($\approx$10 kev) levels having $J=\frac{3}{2}^-$, $\Gamma=80$ kev and $J=\frac{7}{2}^-$, $\Gamma=40$ kev. Figure 4 gives our $C^{14}(p,n)$ center-of-mass neutron yields in this region of excitation for three center-of-mass angles. Strong interference between levels of opposite parity is indicated since the yields are not symmetrical about 90°. Since the neutron yield from the $J=\frac{7}{2}^-$ level should be very small due to the low penetrability of the F-wave neutron, this interference is probably between the $J=\frac{3}{2}^-$, $\Gamma=80$-kev level and the broad $J=\frac{1}{2}^+$ level at higher energy as discussed by Lee and Schiffer. This interpretation is in agreement with the experimental width of our anomaly.

No explanation has been found for the fact that resonances at 13.71-, 14.08-, 14.17-, and 14.63-Mev excitation were observed in the $B^{11}+\alpha$ reactions, but are not evident in our work.

[7] These data were obtained by C. H. Johnson, H. B. Willard, J. K. Bair, and J. D. Kington. Details of this work may be found in the Oak Ridge National Laboratory Report ORNL-1365 (unpublished).

[8] T. W. Bonner, A. A. Kraus, Jr., J. B. Marion, and J. P. Schiffer, Phys. Rev. **102**, 1348 (1956).