$$C_{44}=C_{4,-4}=0.169B_2^2-0.0387B_0B_2^2-0.00046B_0^3B_2+0.0062B_0^2B_2^2+0.001B_0B_2^3+0.006B_2^4-0.000045B_0^4B_2-0.00044B_0^3B_2^2-0.00026B_0^2B_2^3-0.00128B_0B_2^4+\cdots,$$

$$C_{60}=0.0097B_0^3+0.0095B_0B_2^2+0.0012B_0^4-0.00063B_0^2B_2^2-0.00029B_2^4+0.00023B_0^5-0.000011B_0^4B_2+0.00032B_0^3B_2^2+0.000021B_0^2B_2^3+0.00013B_0B_2^4+\cdots,$$

$$C_{62}=C_{6,-2}=0.016B_0^2B_2+0.0027B_2^3-0.00175B_0B_2^3-0.001B_0^3B_2-0.000009B_0^5+0.000235B_0^4B_2+0.000013B_0^3B_2^2+0.00057B_0^2B_2^3+0.000048B_2^5+\cdots,$$

$$C_{64}=C_{6,-4}=0.018B_0B_2^2-0.0008B_0^2B_2^2-0.00063B_2^4-0.00002B_0^4B_2+0.00022B_0^3B_2^2+0.000042B_0^2B_2^3+0.00026B_0B_2^4+0.000083B_2^5+\cdots,$$

$$C_{66}=C_{6,-6}=0.016B_2^3-0.0021B_0B_2^3-0.000037B_0^3B_2^2+0.0004B_0^2B_2^3+0.000074B_0B_2^4+0.0006B_2^5+\cdots,$$

$$C_{80}=0.00058B_0^4+0.00113B_0^2B_2^2+0.0001B_2^4+0.000075B_0^5-0.00011B_0^3B_2^2-0.00011B_0B_2^4+\cdots,$$

$$C_{82}=C_{8,-2}=0.00117B_0^3B_2+0.00058B_0B_2^3+0.000079B_0^4B_2-0.00018B_0^2B_2^3-0.000021B_2^5+\cdots,$$

$$C_{84}=C_{8,-4}=0.0015B_0^2B_2^2+0.00017B_2^4-0.000092B_0^3B_2^2-0.00015B_0B_2^4+\cdots,$$

$$C_{86}=C_{8,-6}=0.00154B_0B_2^3-0.00013B_0^2B_2^3-0.00005B_2^5+\cdots,$$

$$C_{88}=C_{8,-8}=0.00146B_2^4-0.00025B_0B_2^4+\cdots,$$

$$C_{10,0}=0.000028B_0^5+0.000071B_0^3B_2^2+0.000013B_0B_2^4+\cdots,$$

$$C_{10,2}=C_{10,-2}=0.000052B_0^4B_2+0.000013B_0^2B_2^3+0.000026B_0B_2^4+0.0000015B_2^5+\cdots,$$

$$C_{10,4}=C_{10,-4}=0.0001B_0^3B_2^2+0.000033B_0B_2^4+\cdots,$$

$$C_{10,6}=C_{10,-6}=0.00011B_0^2B_2^3+0.000033B_0B_2^4+\cdots,$$

$$C_{10,8}=C_{10,-8}=0.00011B_0B_2^4+\cdots,$$

$$C_{10,10}=C_{10,-10}=0.00011B_2^5+\cdots.$$

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Gamma Decay of the 7.57-MeV Level of N^{15}†*

W. W. Eidson and R. D. Bent
Indiana University, Bloomington, Indiana
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The $C^{12}(\alpha,p\gamma)N^{15}$ reaction was studied using particle-gamma coincidence techniques and the 22-MeV alpha-particle beam of the Indiana University cyclotron. The 7.57-MeV level of N^{15} is observed to decay by gamma emission to either the 5.28- or 5.30-MeV level. An upper limit of 10% is placed on the intensity of the ground-state branch. This information, together with the results of other experiments, suggests a spin and parity assignment of $\frac{5}{2}^+$ or $\frac{7}{2}^+$ for the 7.57-MeV level, which is consistent with shell-model predictions.

I. INTRODUCTION

The shell-model calculations of Halbert and French[1] have been successful in predicting many of the properties of the positive-parity states of N^{15}: a spin of $\frac{5}{2}^+$ or $\frac{7}{2}^+$ is predicted for the 7.57-MeV level. The $N^{14}(d,p)$ stripping reaction studies of Green and Middleton[2] and Warburton and McGruer[3] indicate that the 7.57-MeV level has positive parity and spin $\leqslant\frac{7}{2}$. The present experiment was undertaken to help determine the spin of the 7.57-MeV level.

II. APPARATUS AND PROCEDURES

Gamma radiation from N^{15} was studied employing the $C^{12}(\alpha,p\gamma)N^{15}$ reaction with the 22-MeV alpha-particle beam of the Indiana University cyclotron. Standard fast-slow coincidence circuitry was arranged so that gamma rays could be studied in time coincidence with charged reaction particles of a selected energy. In this way it was possible to study the decay modes of individual levels resolved by the particle detector. As a check on the interpretation of the coincidence gamma-ray spectra, measurements were also made of charged-

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* A preliminary report of this work was given at the New York meeting of the American Physical Society, 1962 [W. W. Eidson and R. D. Bent, Bull. Am. Phys. Soc. **7**, 71 (1962)].
[1] E. C. Halbert and J. B. French, Phys. Rev. **105**, 1563 (1957).
[2] T. S. Green and R. Middleton, Proc. Phys. Soc. (London) **A69**, 28 (1956).
[3] E. K. Warburton and J. N. McGruer, Phys. Rev. **105**, 639 (1957).

particle spectra in time coincidence with gamma rays of a selected energy.

Two types of particle detectors were used: (1) a CsI(Tl) crystal, 0.015-in. thick and $\frac{3}{4}$ in. in diameter, mounted on a DuMont type 6291 photomultiplier tube; (2) a Hughes 1-cm^2 diffused-junction, solid-state detector connected directly to a low-noise, charge-sensitive preamplifier.[4] Since the pulse height from a solid-state detector is proportional only to the energy loss of the charged particle in the detector, whereas the pulse height from the CsI crystal is dependent on the charge of the stopped particle,[5] using the two detectors allows one to distinguish alpha particles from protons and deuterons by observing the change in relative pulse heights when the same spectrum is recorded with the two different detectors.

At 22-MeV (lab) alpha-particle bombarding energy on the light nucleus C^{12}, the only reactions which can yield charged particles in coincidence with gamma rays are $C^{12}(\alpha,\alpha'\gamma)$ and $C^{12}(\alpha,p\gamma)N^{15}$ (ground state $Q=-4.96$ MeV). The (α,d) reaction has such a large negative Q value ($Q=-13.57$ MeV) that there is barely enough energy to populate the first excited state of N^{14}; this level is assigned $T=1$ and should not be populated in this reaction.[6] Thus by the interchange of the particle detection systems it is possible to determine whether an unassigned charged-particle group which is in coincidence with gamma radiation is due to protons or to alpha particles. Except for particle identification, the solid-state detector was used for the coincidence spectra shown in this paper because of its superior stability and inherently higher resolution.

The scattering chamber was an 8-in. diam right-circular cylinder. Targets were inserted through the lid into the center of the chamber. Either type of particle detector could be inserted into a well in the lid of the chamber. By rotating the lid on ball-bearings, the angle of the particle detector could be varied without loss of vacuum in the chamber.

The gamma-ray detector was a 3- ×3-in. NaI (Tl) crystal mounted on a DuMont type 6363 photomultiplier tube. This assembly was mounted on a dolley, outside the vacuum system, and was constrained to rotate about the target center, in the reaction plane. The solid angle subtended by the gamma detector was 2.5% of the total sphere.

Several precautions were taken to minimize the gamma-ray background. (1) The internal cyclotron beam was degraded by reducing the opening in the arc cone from a normal size of $\frac{1}{8}$- $\times\frac{1}{4}$-in. to a $\frac{1}{16}$-in. diam hole. This permitted very small beam currents to be incident on the target (0.001 μA) while maintaining stable arc and main oscillator operation and reducing background produced by collimation. (2) The scattering chamber and both detectors were enclosed in a concrete hut with walls 15-in. thick. (3) All beam-defining collimators and the Faraday cup were constructed of high-Z materials (lead or tantalum), were located outside the gamma-ray hut, and were shielded from the gamma detector by at least 10 in. of lead. (4) All sections of beam pipe in the experimental area were lined with $\frac{1}{16}$-in. thick lead sheet to prevent scattered alphas from coming in contact with the brass of the beam pipe. Background counts in the gamma-ray crystal were essentially negligible under the above conditions.

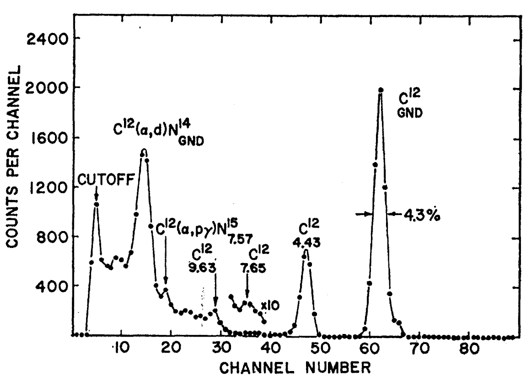

FIG. 1. Charged-particle spectrum obtained with a 1-cm^2 solid-state detector from the bombardment of a 1.6-mg/cm^2 self-supporting carbon foil with 22-MeV alpha particles. Detection angle 42° (Lab).

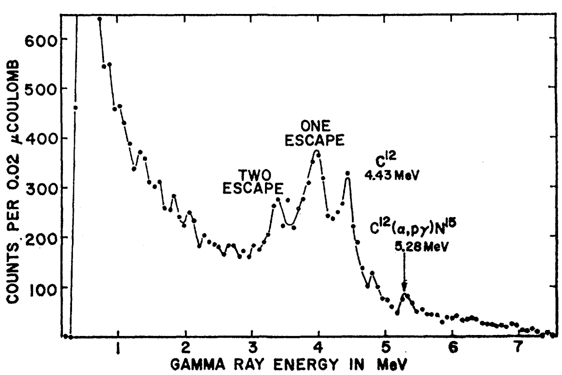

FIG. 2. Gamma-ray spectrum obtained with a 3- ×3-in. NaI (Tl) crystal from the bombardment of a 1.6-mg/cm^2 self-supporting carbon foil with 22-MeV alpha particles. Gamma detector located at 90° with respect to the beam direction.

III. EXPERIMENTAL RESULTS

Figure 1 shows the charged-particle spectrum obtained from the bombardment of a 1.6-mg/cm^2 self-supporting carbon target with 22-MeV alpha particles. This spectrum was recorded with the Hughes solid-state detector located at an angle of 42° with respect to the beam direction. The relatively poor energy resolution was the result of the large solid angle necessary for the coincidence measurements. The inelastic alpha groups

[4] Tennelec Instrument Company, Oak Ridge, Tennessee.
[5] R. A. Peck, Jr., H. P. Eubank, and T. Lowe, Rev. Sci. Instr. **30**, 703 (1959).
[6] B. G. Harvey and J. Cerny, Phys. Rev. **120**, 2162 (1960).

are unambiguously identified with the known[7] excited states of C^{12} at 4.43, 7.65, and 9.63 MeV by the kinematical energy shifts in angular distribution measurements. The identification of the ground-state deuteron group from the $C^{12}(\alpha,d)N^{14}$ reaction and the proton group from the 7.57-MeV level of N^{15} in the $C^{12}(\alpha,p\gamma)N^{15}$ reaction is made through: (1) direct energy calculation and the kinematical energy shift in the angular distributions; (2) the arguments, stated in Sec. II of this report, that only the ground state of N^{14} can be populated in the (α,d) reaction; (3) the assumption that higher-energy proton groups from lower-lying levels of N^{15} pass entirely through the thin detector and contribute to lower-energy pulses; (4) the results of the coincidence measurements which are to be presented later in this report. It is felt that (4) is the strongest argument for the assignment of the particle groups, as accurate energy calibration of the solid-state counter proved difficult for low-energy particles. That the two

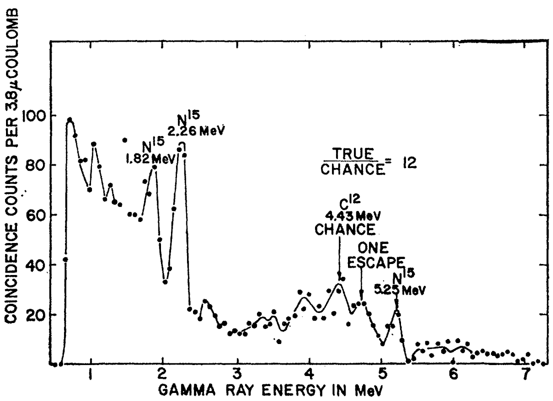

FIG. 3. Uncorrected gamma-ray spectrum from $C^{12}+\alpha$ coincident with protons from the 7.57-MeV excited level of N^{15}. Collection time 3 h, 15 min.

groups in question are not alphas is definitely established by the fact that their pulse height increases by a factor of 2 relative to the alpha pulses when the CsI crystal is substituted as the particle detector. Recoil protons from hydrogen contamination of the target pass through the thin counter but deposit sufficient energy to be also included under the peak labeled as $C^{12}(\alpha,d)N^{14}$.

Figure 2 is a gamma-ray spectrum, without coincidence requirements, obtained from the bombardment of a 1.6-mg/cm^2 self-supporting carbon target with 22-MeV alpha particles. This spectrum was taken with the 3- $\times$3-in. NaI crystal located at 90° to the beam direction and in the plane of the beam and the particle detector. No corrections for background were made on this or on other spectra shown because such effects were negligibly small. The strong 4.43-MeV ground-state transition from the first excited level of C^{12} is the only prominent gamma ray. There is weak evidence for a

[7] F. Ajzenberg and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

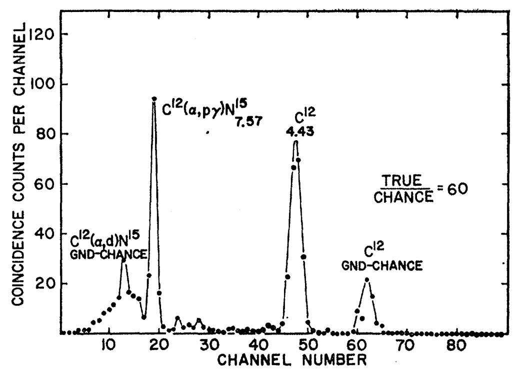

FIG. 4. Uncorrected charged-particle spectum from $C^{12}+\alpha$ coincident with gamma rays in the energy interval 1.8 to 2.8 MeV. Collection time 1 h, 40 min.

5.25-MeV line, which is attributed to the $C^{12}(\alpha,p\gamma)N^{15}$ reaction through the results of the coincidence spectra, but little other structure is seen. The 4.43-MeV line and the gamma rays from a Na^{22} source (1.28 and 0.511 MeV) were used for energy calibration of the gamma-ray spectra.

Figure 3 shows the gamma-ray spectrum from $C^{12}+\alpha$ taken in coincidence with the particle group which had been tentatively identified as due to protons from the 7.57-MeV level of N^{15} (see Fig. 1). Corrections for background and accidental coincidences have not been made. The total time required for collection of these data was 3 h 15 min. It is noticed that there is a marked difference between this spectrum and the singles spectrum of Fig. 2. The 4.43-MeV line is now considerably weaker and is attributed to chance; strong 2.26- and 5.25-MeV gamma rays are evident. The 1.82-MeV line is mainly the Compton peak of 2.26-MeV gamma rays. Some of the 1.88-MeV cascade between the 7.16- and 5.28-MeV levels of N^{15}, which has been previously reported by Thompson,[8] may also be contributing to this peak. The width of the coincidence window allowed for inclusion of some of the proton group corresponding to the 7.16-MeV level. Taking into account the energy dependence of the efficiency and the peak-to-total ratios for a 3- $\times$3-in. NaI (Tl) crystal,[9] the intensities of the 5.25- and 2.26-MeV gamma rays are found to be approximately the same.

To check these results, Fig. 4 shows the charged-particle spectrum taken in coincidence with the 2.26-MeV gamma radiation present in Fig. 3. The peak which had been labeled as due to $C^{12}(\alpha,p\gamma){N^{15}}_{7.57}$ in Fig. 1 is now quite sharp and is clearly in coincidence with 2.26-MeV gamma radiation. As the coincidence window also included some of the Compton distribution of the 4.43-MeV gamma ray from $C^{12}(\alpha,\alpha'\gamma)$, the inelastic alpha-particle group populating that level is also

[8] L. C. Thompson, Phys. Rev. **96**, 369 (1954).

[9] R. L. Heath, *Scintillation Spectrometry Gamma-Ray Spectrum Catalogue* (Phillips Petroleum Company, Atomic Energy Division, Idaho Falls, Idaho, 1957), Atomic Energy Commission Publication TID-4500, (unpublished), 13th ed.

seen. A comparison of Fig. 4 with Fig. 1 yields a true-to-chance ratio of 60 to 1. A coincidence spectrum similar to Fig. 4 was also taken using a CsI(Tl) crystal for particle detection. This spectrum showed a particle peak coincident with the 2.26-MeV gamma radiation which was a factor of two larger in pulse height relative to the alpha particles, thus confirming the assertion that this charged-particle peak is due to protons.

IV. DISCUSSION OF EXPERIMENTAL RESULTS

The coincidence spectra of Figs. 3 and 4 clearly show that a proton group from the $C^{12}(\alpha,p\gamma)N^{15}$ reaction is in coincidence with gamma radiation of 2.26±0.04 MeV and 5.25±0.1 MeV. Further, the energy of the proton group plus the sum of the gamma-ray energies indicate unambiguously that the 7.57-MeV level of N^{15} is decaying by cascade gamma rays through one of the well-known levels at 5.28 or 5.30 MeV. It is impossible to determine from the gamma-ray energies alone through which of these levels the cascade proceeds. From Fig. 3 an upper limit of 10% is placed on the intensity of the ground-state branch from the 7.57-MeV level. This result is consistent with the work of Bashkin[10] on the reactions $B^{10}(Li^6,p)N^{15}$ and $B^{11}(Li^6,d)N^{15}$. These results are summarized in Fig. 5, which shows the energy-level scheme of N^{15}. This level scheme is essentially that compiled by Ajzenberg and Lauritsen[11] with a few recent additions which will be described later. The gamma rays shown in the figure represent the N^{15} transitions observed in the present experiment.

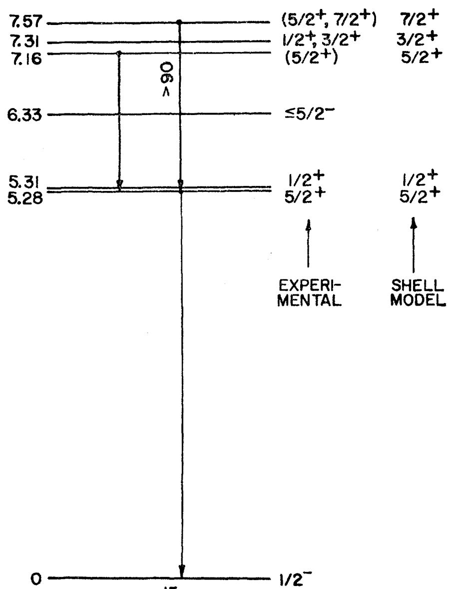

FIG. 5. Energy-level diagram of N^{15} including experimental and shell-model spin and parity assignments, and the gamma-ray transitions observed in the present experiment.

The data of Green and Middleton[2] and Warburton and McGruer[3] indicate that the 7.57-MeV level has positive parity and spin $\leqslant\frac{7}{2}$. The weakness of the ground-state transition from the 7.57-MeV level suggests that the spin of this level is greater than $\frac{3}{2}$, since otherwise the energy-favored $E1$ transition to the ground state should be more intense. This argument is based on single-particle transition probabilities and the systematics of transition probabilities for light nuclei.[12] It seems likely, therefore, that the 7.57-MeV level is $\frac{5}{2}^+$ or $\frac{7}{2}^+$.

V. SHELL-MODEL INTERPRETATION OF RESULTS

The shell-model calculations of Halbert and French[1] predict a spin of $\frac{5}{2}^+$ for the 7.57-MeV level of N^{15} and $\frac{7}{2}^+$ for the 7.16-MeV level, but the assignments could be interchanged.[1] Since the work of Hebbard[13] suggests a spin of $\frac{5}{2}^+$ for the 7.16-MeV level, then the shell model predicts a probable $\frac{7}{2}^+$ for the 7.57-MeV level. With such an assignment, the transition to the $\frac{5}{2}^+$ level at 5.28 MeV is expected to dominate strongly over the direct transition to the $\frac{1}{2}^-$ ground state. The present experimental results are consistent with this prediction.

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[10] S. Bashkin (private communication).

[11] F. Ajzenberg-Selove and T. Lauritsen, *Ann. Rev. Nuclear Sci.* **10**, 419 (1960).

[12] D. H. Wilkinson, in *Nuclear Spectroscopy* edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), pp. 852–889.

[13] D. F. Hebbard, Nuclear Phys. **19**,511 (1960).