Radiative Capture of Protons by N^{14}†

S. BASHKIN, R. R. CARLSON, AND E. B. NELSON
State University of Iowa, Iowa City, Iowa
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The 277-kev resonance for the production of O^{15} in its 7.61-Mev state was excited by proton bombardment of a thick TiN target. A three-crystal, scintillation spectrometer resolved gamma rays of 5.25±0.1 Mev, 6.10±0.1 Mev, and 6.65±0.15 Mev, with relative intensities of 25±6, 100, and 40±10, respectively. Direct ground state transitions have a relative intensity of less than 5. The total radiative capture yield in nitrogen is $(2.7\pm0.6)\times10^{-11}$ reaction per proton. The intensity ratio of 6.10-Mev radiation to 5.25-Mev radiation, measured with a single-crystal spectrometer, is 7±3 percent lower at 90° to the beam than at 0°. The asymmetry eliminates pure *s*-wave capture. It is concluded that the capture state has spin 5/2 and decays by dipole emission to the first three excited states of O^{15}.

INTRODUCTION

RADIATIVE capture and elastic scattering are the only nuclear reactions which can occur in the bombardment of N^{14} by protons with less than 3.1 Mev of energy. Tangen[1] has shown radiative capture to be resonant at a proton energy of 277 kev over a range of less than 2 kev. This corresponds to an excited state at 7.61 Mev in O^{15}. Duncan and Perry[2] obtained the $N^{14}(p,\gamma)O^{15}$ excitation curve by observing the positron activity from the short-lived residual nucleus. They suggested that the 277-kev resonance is excited by *s*-wave protons, giving a spin of $\frac{1}{2}^+$ or $\frac{3}{2}^+$ to the 7.61-Mev level in O^{15}.

Johnson, Robinson, and Moak[3] used a single-crystal, scintillation spectrometer to measure the energies of the gamma rays produced at the 277-kev resonance in the $N^{14}(p,\gamma)O^{15}$ reaction. The observed gamma rays were attributed to transitions from the capture state to the ground state by way of levels at 6.84 Mev, 6.19 Mev, and 5.27 Mev. Direct decays from the 7.61-Mev state to the ground state were not observed. These excited states have also been observed[4,5] in the $N^{14}(d,n)O^{15}$ reaction. Application[5] of Butler's stripping theory to the angular distributions of the neutrons in this reaction indicated that a state at about 6.8 Mev has a spin of $\frac{1}{2}^+$ or $\frac{3}{2}^+$. Assignments to the other states were less certain but included the suggestion of $\leq 5/2^-$ for a level at 7.48 Mev. The position of this level was sufficiently uncertain that it could be identical[6] with the 7.61-Mev level in O^{15}. Bent *et al.*[7] have attributed gamma rays of 6.81 Mev, 6.12 Mev, and possibly 5.26 Mev, to the reaction $N^{14}(d,n)O^{15}$.

The levels found in the foregoing experiments are in approximate correspondence with levels in the mirror nucleus, N^{15}, as located[8] in the $N^{14}(d,p)N^{15}$ reaction. However, N^{15} shows closely spaced levels near 5.3 Mev and 7 Mev which, if mirrored in O^{15}, have not been resolved in that nucleus.

The present experiment was an investigation of the absolute gamma ray and positron yields and the anisotropy of the gamma rays from the 277-kev resonance in the radiative capture of protons by N^{14}. It was hoped that these measurements would reduce the possible spin and parity assignments to the 7.61-Mev and lower excited states in O^{15}.

EXPERIMENTAL ARRANGEMENT

Protons, accelerated in a 500-kv Cockcroft-Walton accelerator and deflected through 90° by a magnetic field, struck a thick target of pressed titanium nitride powder, isolated from the vacuum pumps by a dry ice and acetone cold trap. Gamma-ray detectors were single-crystal and three-crystal scintillation spectrometers, employing NaI(Tl) crystals and RCA5819 photomultiplier tubes. The three crystal spectrometer[9] consisted of three crystals in a row, the center crystal being 2 in. long by $1\frac{1}{2}$ in. in diameter and the two side crystals being 1 in. long by $1\frac{1}{2}$ in. in diameter. Distance from target to nearest center-crystal face was $2\frac{1}{2}$ in. The pulses from the center detector were analyzed by a 10-channel pulse-height analyzer[10] only when a triple coincidence between the three detectors occurred. By this means, pulses from the center detector were measured when a pair was produced in the center crystal and both annihilation quanta escaped. The single-crystal spectrometer consisted of the center detector of the three-crystal spectrometer and the 10-channel pulse-height analyzer. Limiters of Elmore's design[11] were used with the single-crystal spectrometer in the study of low-energy gamma rays in the presence of high-energy radiation.

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[2] D. B. Duncan and J. E. Perry, Phys. Rev. **82**, 809 (1951).
[3] Johnson, Robinson, and Moak, Phys. Rev. **85**, 930 (1952).
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[6] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952); Revs. Modern Phys. **27**, 77 (1955). We wish to thank Professor Lauritsen for a preprint of the latter paper.
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[9] Carlson, Geer, and Nelson, Phys. Rev. **94**, 1311 (1954).
[10] W. C. Johnstone, Nucleonics **11**, No. 1, 36 (1953).
[11] W. C. Elmore, Rev. Sci. Instr. **20**, 963 (1949).

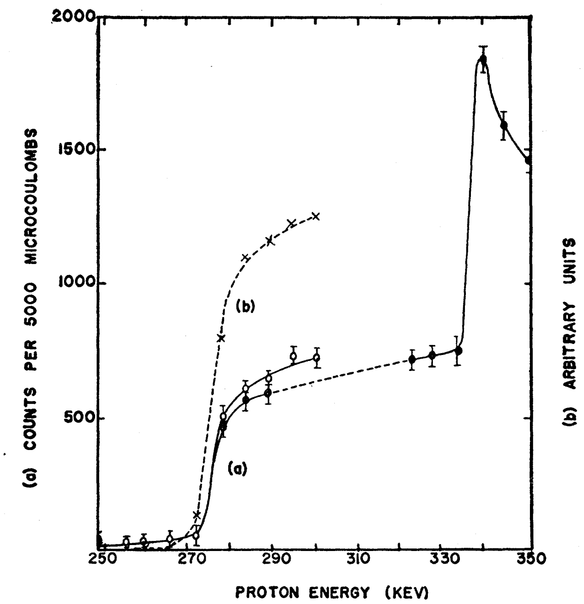

FIG. 1. (a) Yield curves of gamma rays of energy above 4.5 Mev for protons on thick TiN. Open circles obtained at outset of experiment; solid points at conclusion of experiment. (b) Yield curve of positrons for protons on thick TiN target.

GAMMA-RAY YIELDS

The solid curves of Fig. 1 illustrate the gamma-ray yield resulting from the proton bombardment of thick, titanium nitride targets for proton energies between 250 kev and 350 kev. Only gamma rays with energies in excess of 4.5 Mev were recorded in the yield curve measurements. The open points were taken at the start, and the solid points at the end, of the experiment. The good agreement of the two curves indicates that the target neither deteriorated nor accumulated any significant amount of surface contaminants during the lengthy bombardment by beams of about 100 μa. Since the O^{15} state at 7.61 Mev is less than 2 kev wide,[1] the range in proton energy over which the step in the yield curve occurs measures the inhomogeneity of the beam energy. This is estimated to be 3 kev. The absolute value of the proton energy was known to within ± 5 kev.

The peak which appears in the gamma-ray yield curve at a proton energy of 340 kev is due to a resonance for the production of 6.13-Mev gamma rays from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction which was induced in fluorine contamination on the beam-defining apertures. For protons of less than 340 kev of energy, the fluorine reaction is some 900 times weaker[12] than at resonance. Its contribution to the measurements of this experiment was negligible.

The energy scale of the scintillation spectrometers was calibrated with the 6.13-Mev gamma ray from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction which supplies a point at 5.11 Mev and with the 2.62-Mev gamma ray from ThC'' which supplies points at 2.62 Mev, 2.11 Mev, and 1.60 Mev. The calibration curve was linear within the accuracy of the measurement which was two percent at 6 Mev.

A single-crystal, scintillation-spectrometer survey of the gamma rays which appeared when 290-kev protons struck the target gave results in good agreement with those of Johnson, Robinson, and Moak.[3] Figure 2 shows the results of a three-crystal, scintillation-spectrometer study, at 0° to the beam, of the high-energy gamma rays arising from 295-kev proton bombardment of titanium nitride. Statistical uncertainties are given by the vertical lines. Three gamma rays are seen in Fig. 2. Their energies, which are 1.02 Mev plus the energy absorbed in the crystal, were measured as 5.25 ± 0.1 Mev, 6.10 ± 0.1 Mev, and 6.65 ± 0.15 Mev. These values agree within the experimental uncertainty with other determinations.[3,7]

In order to estimate the relative intensities of these gamma rays, the pulse-height distribution in Fig. 2 must be separated into the contributions made by each of the gamma rays. Background contributions from accidental triple coincidence and true triple coincidence from cascade decay were found to be negligible. The pulse-height distribution of the pure 6.13-Mev gamma ray from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction was taken as a model for the pulse-height distributions of the three gamma rays observed above. Figure 3 shows the spectrum of Fig. 2 decomposed into its constituent parts. Figure 3 also shows the measured pulse-height distribution of the fluorine gamma ray. The relative intensities were assumed to be proportional to the relative peak heights after correcting for pair-production cross section. Choosing the intensity of the 6.10-Mev gamma

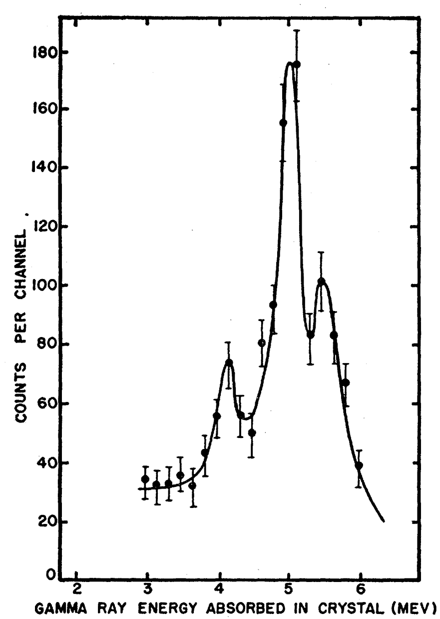

FIG. 2. Three-crystal, scintillation spectrometer analysis of gamma rays from $N^{14}(p,\gamma)O^{15}$ reaction for 295-kev protons on thick TiN.

[12] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).

ray as 100, the 5.25-Mev gamma ray has an intensity of 25±6, and the 6.65-Mev gamma ray an intensity of 40±10.

The pulse-height distribution was also measured with poorer resolution but increased detection efficiency by moving the spectrometer closer to the target. From this measurement, the intensity of the direct transition from the capture state to the ground state is estimated to be less than 5 percent that of the 6.10-Mev transition.

Comparison of the 6.10-Mev gamma-ray yield with that of the known[12] absolute yield of the fluorine gamma ray from a thick, calcium fluoride target at the 340-kev resonance, gave an absolute 6.10-Mev gamma-ray yield of $(4.5\pm1.1)\times10^{-12}$ gamma per proton for 295-kev protons on thick titanium nitride. By interpolating in the stopping power data of Warshaw[13] to obtain the stopping powers of nitrogen and titanium, and using the above relative intensities, the total absolute yield of the three $N^{14}(p,\gamma)O^{15}$ gamma rays for 295-kev protons on thick nitrogen is $(2.7\pm0.6)\times10^{-11}$ gamma per proton. Statistics, resolution, and uncertainties in the stopping powers contribute to the quoted error.

GAMMA-RAY ANISOTROPY

The possibility that the gamma rays might be distributed anisotropically was investigated with a single-crystal scintillation spectrometer placed alternately at 0° and 90° to the proton beam. The necessity of acquiring good statistics made it impossible to use the good resolution, but low efficiency, three-crystal, scintillation spectrometer. Hence the interpretation of the observed spectrum was complicated by the multiplicity of peaks produced in a single-crystal scintillation spectrometer by gamma rays of pair-producing energies. In this case, the one-escape peak of the 5.25-Mev gamma ray is not obscured by any other peaks, although there is, of course, a background due to degraded gamma rays. Similarly, the two-escape peak of the 6.10-Mev gamma ray is well isolated from other peaks, and the one-escape peak of the 6.10-Mev gamma ray is only slightly contaminated by the lower intensity, two-escape peak of the 6.65-Mev gamma ray. Consequently, the gamma rays were observed only in the energy range which encompasses those peaks.

In order to obtain an adequate yield of gamma rays a 100-μa proton beam and a $\frac{1}{4}$-in. diameter beam spot were used. The NaI(Tl) crystal of the scintillation detector was placed a distance of $2\frac{1}{2}$ in. from the target. Under these conditions an accurate measurement of the absolute angular distribution of the gamma rays could not be made. Measurements were, therefore, made on the difference in relative intensity of the 5.25-Mev and 6.10-Mev gamma rays when the angle of observation was changed from 0° to 90°. An isotropic distribution, which must follow s-wave capture and which might occur even for higher angular momentum waves, would give rise to the same ratio of intensities

[13] S. D. Warshaw, Phys. Rev. **76**, 1759 (1949).

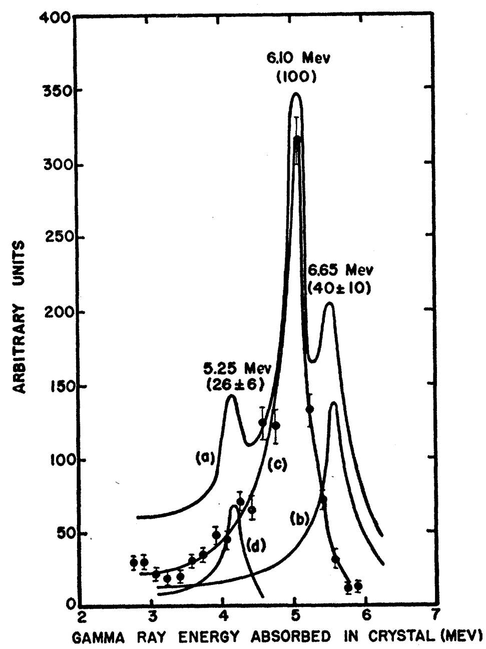

FIG. 3. Separation of high-energy spectrum of $N^{14}(p,\gamma)O^{15}$ gamma rays into individual components. (a) Total curve. (b) 6.65-Mev line. (c) 6.10-Mev line. (d) 5.25-Mev line. Points and statistics are shown for the fluorine measurement.

of the 6.10-Mev gamma rays to the 5.25-Mev gamma rays at the two angles. Unequal ratios would mean that at least one of the gamma rays under study was not distributed with spherical symmetry. The argument is not altered if the gamma rays are emitted in cascade processes.

Since the target was pressed onto a thin copper end-plate of a thin-walled brass tube and was normal to the beam, the emergent gamma rays did not traverse the same quantity of matter when viewed at 90° as when viewed at 0°. The difference in absorption of the 5.25-Mev and 6.10-Mev gamma rays emerging in the two directions was calculated and the effect on the anisotropy measurement was found to be negligible.

The 90° data were normalized to the 0° data at the one-escape peak of the 5.25-Mev gamma ray, so that any anisotropy would appear as a difference in the heights of both the one- and two-escape peaks of the 6.10-Mev gamma ray as measured at the two angles. Figure 4 shows the results. The dotted curve represents the 0° data and the solid curve, the 90° data. The 6.10-Mev gamma ray shows a definite decrease in intensity, relative to that of the 5.25-Mev radiation, as the angle of observation is altered from 0° to 90°. This decrease is estimated at 7±3 percent.

POSITRON MEASUREMENTS

There are certain advantages to measuring the absolute yield of the $N^{14}(p,\gamma)O^{15}$ reaction from the positron activity aside from the fact that it provides an independent check on the gamma ray results. Measure-

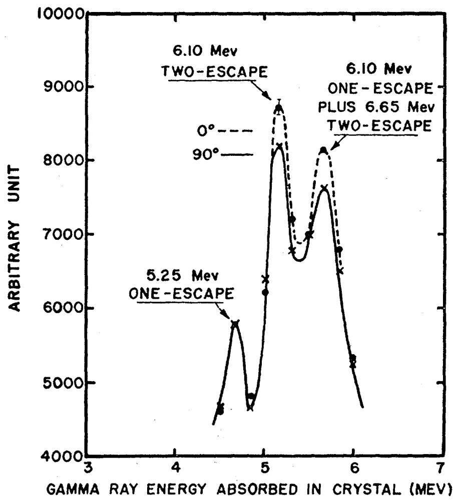

FIG. 4. Single-crystal spectra, at 0° and 90°, of high-energy gamma rays from 295-kev protons on thick TiN. Curves were normalized at 5.25-Mev one-escape peak.

ments can be taken with the accelerator off, thereby reducing background. The detection efficiency for the annihilation radiation is much greater than for the high energy gamma rays. Finally, the positron yield is greater than the yield of any one gamma ray. Disadvantages include the possible loss of O^{15} from the target, and uncertainties in the degree of saturation of the activity because of fluctuations in the beam current. Neither of these disadvantages affects the gamma-ray work.

The positron measurements necessitated knowing the O^{15} half-life. After bombarding the target for ten minutes with a 75-μa proton beam stable to ± 1 μa, the accelerator was turned off and a $\frac{3}{4}$ in. thick brass plug was inserted next to the bombarded face of the target to define the volume in which annihilation occurs. A fraction of a second was consumed by the operations which preceded starting the counters. The single-crystal scintillation spectrometer detected the annihilation radiation from the positrons. Counts in the peak of the pulse-height distribution corresponding to annihilation radiation were accumulated in 25-second intervals, separated by 5-second periods during which the data were recorded and the scaler cleared. The decay was followed for ten minutes. Semilog plots of the data were fitted with straight lines based on least squares analyses. A half-life of 121 ± 3 seconds was obtained which agrees, within experimental error, with previous measurements.[14–16] The uncertainty in the present measurement derives almost entirely from statistics.

The dotted curve of Fig. 1 shows the yield curve for the positron activity. These data represent the numbers of counts under the total absorption peak of the annihilation radiation accumulated in a 260-second interval following a ten minute bombardment of the target at each energy. The positron yield exhibits a sharp step at the same incident energy as the gamma ray yield. The rise above the resonance, which was also reported by Tangen,[1] may be due to the fact that less O^{15} escapes from the target as the bombarding energy is raised since the reaction occurs deeper in the target material.

In order to determine the absolute yield of positrons, the efficiency of the spectrometer for detecting annihilation radiation from the target was measured. The method has been previously described.[17] In this case, a Na^{22} positron source was painted in a $\frac{1}{4}$ in. diameter spot on a 2 mm thick, 1 cm^2 anthracene crystal, which was mounted on an RCA5819 photomultiplier tube. The geometry was arranged to duplicate that of the $N^{14}(p,\gamma)O^{15}$ experiment. Coincidences were counted between the positrons, as detected in the anthracene, and their annihilation radiation, as detected in a NaI(Tl) crystal. Only those pulses corresponding to the total absorption of the annihilation radiation were used to measure the desired efficiency. The Na^{22} positrons are in coincidence[6] with a 1.28-Mev gamma ray from the daughter nucleus as well as with their own annihilation radiation. Since the 1.28-Mev gamma ray produced only a small, roughly constant background over the width of the annihilation radiation total absorption peak, corrections for it were easily made.

Positrons resulting from a 10-minute bombardment by a 295-kev 3.5-μa proton beam, stable to ± 0.2 μa, were counted with the scintillation detector of known efficiency for annihilation radiation. Correcting for the stopping power of the titanium in the target in the same way as in the high energy gamma ray work, an absolute yield was obtained for a thick nitrogen target of $(2.2\pm 0.4)\times 10^{-11}$ positron per proton. The fact that this value is lower than the value obtained from the gamma ray measurement may be due, at least partly, to the loss of O^{15} from the target during the bombardment. Tests made with beams up to 75 μa showed that the apparent yield decreased 10 percent at the highest beam strength. On this basis, the gamma-ray yield data are believed to be more reliable. These results are to be compared with the absolute yield of $(3.5\pm 0.4)\times 10^{-11}$ positron per proton reported by Duncan and Perry.[2]

YIELDS BELOW RESONANCE

The significance of $N^{14}(p,\gamma)O^{15}$ reaction in stellar processes has been discussed by Salpeter.[18] Attempts were therefore made to measure the absolute yield for 255-kev protons by observing both the positron activity and the high energy gamma rays. The single-crystal spectrometer pulse-height distribution in the region corresponding to high energy gamma rays was meas-

[14] V. Perez-Mendez and H. Brown, Phys. Rev. **76**, 689 (1949).
[15] Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).
[16] G. T. Seaborg and I. Perlman, Revs. Modern Phys. **20**, 585 (1948).
[17] S. Bashkin and R. R. Carlson, Phys. Rev. **97**, 1245 (1955).
[18] E. E. Salpeter, Ann. Rev. Nuc. Sci. **2**, 41 (1953).

ured. The yield of high-energy gamma rays below resonance is less than 2 percent of the resonant yield. No positron activity was observed after 10-minute bombardment but the possible loss of O^{15} from the target makes an estimate of an upper limit unreliable.

DISCUSSION

The similar yield curves for the positrons and gamma rays and the measured half-life clearly identify the high energy gamma rays as originating in O^{15}. Spin and parity assignments to the capture and lower levels of O^{15} can be made on the basis of the present results together with previous work. An energy level diagram of the O^{15} nucleus is shown in Fig. 5. The three high-energy gamma rays observed in this experiment are indicated as proceeding from excited states in O^{15} at the corresponding energies. These excited states are taken to be the same states as seen in the $N^{14}(d,n)O^{15}$ work.[5] The spin of the 6.65-Mev state is thereby limited to $\frac{1}{2}^+$ or $\frac{3}{2}^+$. The ground-state spin of O^{15} is assumed to be $\frac{1}{2}^-$, like that of the ground state[6] of the mirror nucleus, N^{15}.

The thick target yield, Y, of this reaction is related to the radiative width, Γ_γ, of the narrow, well-isolated capture level, by the relation,

$$Y=(2\pi^2\lambda\!\!\!^-{}^2/\epsilon)\omega\Gamma_\gamma,$$

where $2\pi\lambda\!\!\!^-$ is the deBroglie wavelength of the proton at resonance, ϵ is the energy loss per atom per cm^2 for protons in nitrogen, and ω is a statistical weight factor equal to $(2J+1)/6$, J being the spin of the capture level. The proton width of the capture level is assumed to be much greater than the radiative width. On the basis of Fig. 5, the total absolute yield of the high-energy gamma rays is the radiative capture yield of the reaction. The present measurements result in

$$\omega\Gamma_\gamma=0.013\pm0.003 \text{ ev}$$

for the level at 7.61 Mev in O^{15}. This agrees with previous work.[19]

The capture level could have spins $\frac{1}{2}^+$ or $\frac{3}{2}^+$ if formed by s-wave proton capture; $\frac{1}{2}^-$, $\frac{3}{2}^-$, or $5/2^-$ from p-wave capture; or $\frac{1}{2}^+$, $\frac{3}{2}^+$, $5/2^+$, or $7/2^+$ from d-wave capture. Higher angular-momentum capture is unlikely. The absence of 7.6-Mev radiation rules out spins $\frac{1}{2}$ and $\frac{3}{2}$ as these would permit dipole transitions to the ground state. Such transitions would be much more intense than the observed low-energy transitions. Pure s-wave capture is also ruled out by the anisotropy observed. Since transitions to the level at 6.65 Mev make up a minimum of 25 percent of the radiative decays of the capture level, the partial width for this transition, regardless of the capture-state spin, must be at least

[19] Woodbury, Hall, and Fowler, Phys. Rev. **75**, 1462(A) (1949).

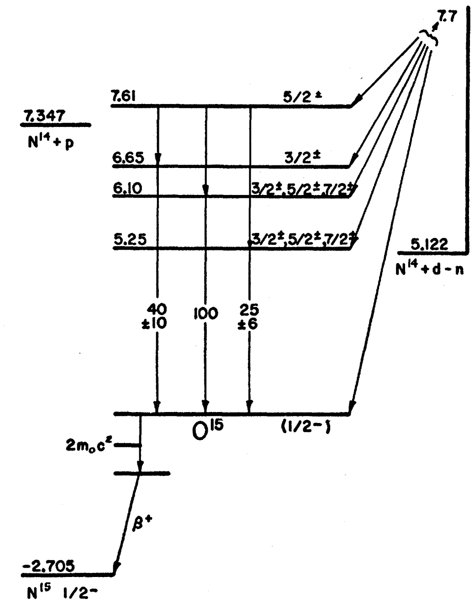

FIG. 5. Energy level diagram for O^{15} for 7.61-Mev and lower states.

0.002 ev. Weisskopf's radiation lifetime formulas[20] show that this value is much too large a radiative width for anything but a dipole transition. Consequently, the 6.65-Mev level is limited to spin $\frac{3}{2}^+$ and the 7.61-Mev level is limited to spins $5/2^+$ or $5/2^-$. If one identifies the 7.61-Mev level with that seen at 7.48 Mev in the $N^{14}(d,n)O^{15}$ experiment,[5] there is a suggestion of odd parity for the 7.61-Mev level.

Detailed consideration, using the Weisskopf radiation lifetime formulas, shows that only dipole transitions occur from the capture state to the three lowest excited states, and that there are very few transitions between those states. The experimental partial radiative widths for decay of the capture state to the states at 6.65 Mev, 6.10 Mev, and 5.25 Mev are, to within 25 percent, 0.003 ev, 0.008 ev, and 0.002 ev, respectively. Figure 5 lists all possible spin values for these states which are consistent with the present work. There is a suggestion from the $N^{14}(d,n)O^{15}$ experiment[5] that the 6.10-Mev level has odd parity and the 5.25-Mev level has even parity.

It should be noted, finally, that the discovery of multiplicity in any of the first three excited states of O^{15} would not effect the conclusions above but would simply mean that one or more of the levels in the multiplet had the spins indicated in Fig. 5.

We would like to thank Professor J. A. Jacobs for his helpful discussions of this experiment. Mr. R. C. Grimm skillfully constructed the target chambers.

[20] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).