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Low-Lying States of N^{16}†

D. H. WILKINSON*
Brookhaven National Laboratory, Upton, New York
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The gamma rays of low energy resulting from the reaction $N^{15}(d,p)N^{16}$ have been studied. Gamma rays of energy 387±5 kev, 268±5 kev, and 118±3 kev are observed by using NaI scintillation techniques, and the presence of another gamma ray of 285±8 kev is inferred. These results indicate states of N^{16} at 118, 285, and 387 kev consistent with earlier studies of heavy particles. The gamma ray of 268 kev results from a cascade from the 387-kev state through the first excited state which is shown to have a lifetime of a few microseconds. By combining these results with the earlier work on heavy particles, it is possible to fix the first excited state of N^{16} as 0− and the third as 1−. The second excited state is with very good probability 2− or 3− with a slight preference for 3−. The ground state is already known to be 2−. These results are in good accord with the theoretical (shell model) predictions of J. P. Elliott.

INTRODUCTION

NITROGEN-16 is a very interesting nucleus. It displays directly the $T=1$ states of O^{16} which is itself one of the direct testing-places and meeting-grounds of the models currently employed in attempts to describe light nuclei. In particular, the alpha-particle model of O^{16} contrasts with the shell model in that it can say nothing significant about the $T=1$ states. Consequently, if the two models should give equally plausible accounts of the low-lying $T=0$ states of O^{16}, a clear choice between them may reasonably be made if the shell model can give a good description of N^{16} about which the alpha-particle model gives no information. The shell-model calculation has been partially carried through,[1] at least in so far as single-particle excitation from the O^{16} ground state goes. It was with the specific objective of testing this calculation that the present investigation was carried out. But N^{16} is also interesting for the experimenter without reference to any theoretical prediction for it has been known for some time to have a level scheme unique in light nuclei: the four lowest states are found within a total energy range of 400 kev followed by at least 850 kev devoid of further levels. The two interests are linked by the fact that this is exactly what the shell model predicts.

LEVELS OF N^{16}

The first indication of the interesting structure of N^{16} came from a study[2] of the reaction $O^{18}(d,\alpha)N^{16}$ which indicated excited states at 116±6, 300±12, and 391 ±12 kev. This structure was confirmed[3] through the reaction $N^{15}(d,p)N^{16}$ which indicated excited states at 0.11, 0.29, and 0.39 Mev. These studies revealed no further levels below an excitation of 1.24 Mev.[2]

Studies of the β decay of N^{16} and of the gamma rays from O^{16} following this decay[4] have shown that the ground state of N^{16} has the character 2−. Such an assignment is reasonable on the basis of the shell model since the promotion of a $1p$ nucleon into the mixed $2s$ and $1d$ shells can give rise to states of spin 0 to 4, all of odd parity. In fact, the detailed shell-model calculation[1] in intermediate coupling predicts that four states of character 0−, 1−, 2−, 3− should lie very close together in N^{16} followed by a relatively large gap. If this prediction is correct, then we should expect the three excited states all to be of odd parity and to have spins 0, 1, and 3 in an unspecified order.

That this prediction may well be correct is suggested by work[5] on the angular distribution of the protons from the reaction $N^{15}(d,p)N^{16}$ using deuterons of 2.8 Mev. These distributions all show pronounced "stripping" characteristics with angular momentum transfers $l=0$, $l=2$ and $l=0$ to the three excited states in order. This shows that all four states in question are indeed of odd parity and that the predicted spins are at any rate possible since the permitted J values for the excited states are respectively 0 or 1, 1, 2 or 3, and 0 or 1. As Zimmermann has remarked,[5] it is less likely that the second excited state should be of spin 1 than 2 or 3 since $J=1$ could be reached through $l=0$, presumably with greater ease, and there is no suggestion of this.[6]

PRESENT INVESTIGATION

It is clear that much more will be learned about these levels if their radiative decay schemes can be determined since the spins are already limited and the parity determined by the stripping observations. To this end we have sought such radiative decay using NaI(Tl) crystals.

The N^{16} was prepared through the same reaction

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* Permanent address: Cavendish Laboratory, Cambridge, England. This work was carried out while the author was Visiting Physicist at Brookhaven National Laboratory during the summer of 1956.

[1] J. P. Elliott, Atomic Energy Research Establishment, Harwell, England (private communication).

[2] R. T. Pauli, Arkiv. Fysik **9**, 571 (1955).

[3] Thirion, Cohen, and Whaling, Phys. Rev. **96**, 850 (1954).

[4] Millar, Bartholomew, and Kinsey, Phys. Rev. **81**, 150 (1951); B. J. Toppel, Phys. Rev. **103**, 141 (1956).

[5] W. Zimmermann, Phys. Rev. **104**, 387 (1956).

[6] As is now well known, the $2s$ and $1d$ shells are rather completely mixed up and it is unlikely that a state of N^{16} of $J=1$ should be so well described by $p^{-1}d$ as to give no detectable $l=0$ stripping.

$N^{15}(d,p)N^{16}$ as was used to limit the spins. Gaseous N^{15} at a pressure of 180 mm Hg and of 99% purity was contained in a thin-walled brass tube of length 5 cm and diameter 1 cm sealed by a nickel foil of thickness 50 micro-inches.[7] Deuterons of energy 3.0 Mev were incident upon the nickel, traversed it and the gas, and were then stopped by the end of the gas cell which was coated on the inner surface with gold to minimize unwanted reactions. Under these conditions, the energy of the deuterons in the gas ranged from roughly 2.6 to 2.9 Mev. This is just the energy used in the proton investigation[5] and so we have been able to use the integrated angular distributions found in that work in order to determine the relative initial populations of the three excited states in our own investigation. Apart from a slight uncertainty involved in extrapolating the proton results beyond $\theta=140°$, the largest angle there studied, this procedure is reliable since it has been shown[5] that the relative proton yields at a fixed angle are constant to $\pm 4\%$ over the range of deuteron energy 2.70 to 2.80 Mev.

The gamma rays issuing from the N^{15} target under these conditions were examined by a NaI(Tl) crystal, a cylinder of length 5.0 cm and diameter 4.5 cm, which was placed at the side of and almost touching the gas target with the two axes of target and crystal parallel. That the radiations came from the N^{15} was checked by replacing it with helium.

Extremely small deuteron currents, less than 5×10^{-5} μa, were used in this work. They were not measured and control was derived from the gamma rays themselves. It was found that the best results were obtained with this close juxtaposition of target and detector. As the detector was moved further from the target, the background counts from deuteron reactions other than in the target, from stray neutrons, and so on increased rapidly in relative importance until, with the crystal about 50 cm from the target, it was difficult to discern the wanted gamma rays at all. However, in the close-up position quite adequate resolution of the low-energy gamma rays was obtained, as will now be described.

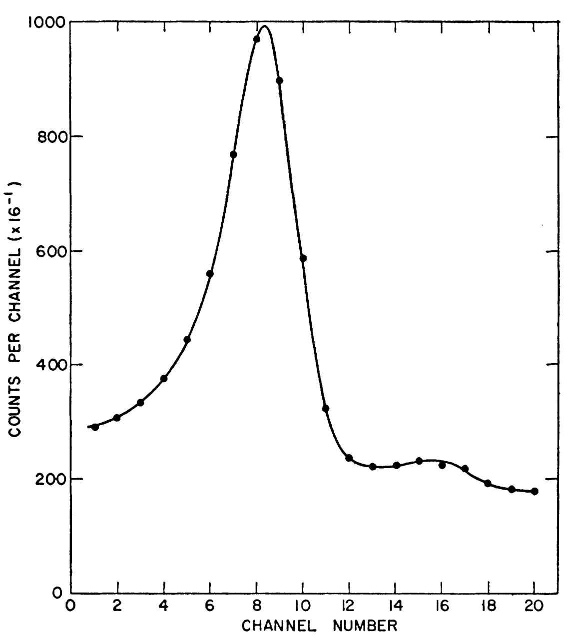

FIG. 1. The 118-kev line is at channel 8. The bump around channel 16 is the 160–170 kev radiation discussed in detail in the text. This spectrum was taken with a bias of 8 channels.

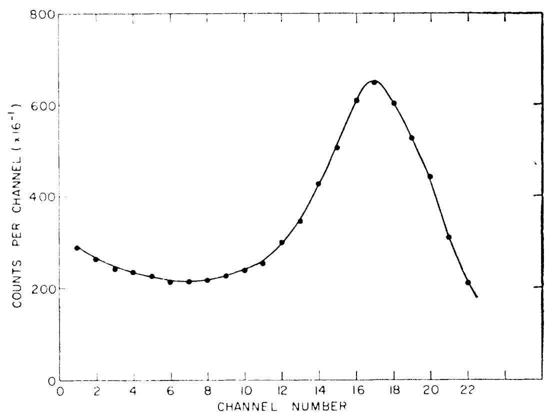

FIG. 2. The 275-kev radiation is at channel 17. This spectrum was taken with a bias of 22 channels.

GAMMA-RAY SPECTRA

Three gamma rays were easily and strongly seen and their energies were accurately measured. This was done many times with annihilation radiation and the 198-kev gamma-ray from In^{114} being used as standards. Typical pulse spectra of these three lines are shown in the first three figures. Figure 1 shows the lowest energy gamma ray, which we measured as having an energy of 118 ± 3 kev and which we believe to correspond to the decay of the first excited state of N^{16} which is located at an energy of 116 ± 6 kev by the particle measurements.[2] There is thus good accord between gamma-ray and particle measurements for this level. Another gamma ray of similar energy could result from a cascade between the second and third excited states but we shall show later that such a transition is weak.

Above this main peak, seen at channel 8 in Fig. 1, there is a small peak or shoulder at channel 16. This was always present and was investigated in great detail. If it were due to a gamma ray its energy would be about 160–170 kev. We shall return to this later.

Figure 2 shows the next gamma ray whose energy we measure as 275 ± 4 kev. As we shall see, it is in fact a superposition of two lines, one the ground-state transition from the second excited state, the other the first member of the cascade from the third excited state through the first. This probable error therefore has no immediate significance.

[7] This N^{15} was very kindly made available by Professor T. I. Taylor of the Chemistry Department, Columbia University, to whom best thanks are expressed.

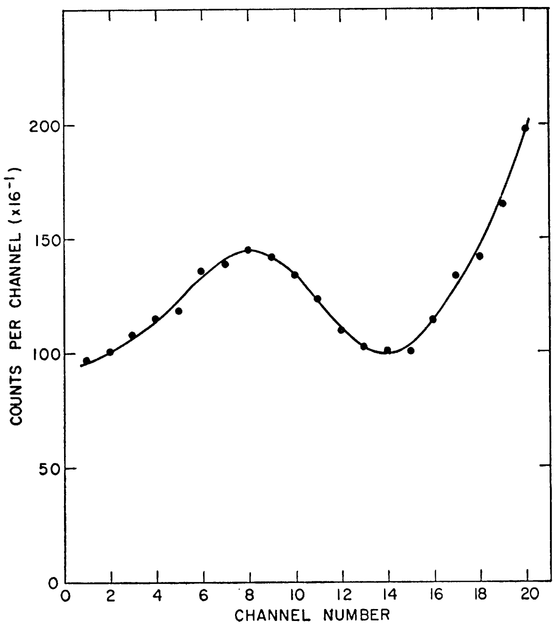

FIG. 3. The 387-kev line is at channel 8. The rise at high channel numbers is due to the 490-kev radiation from F^{17}—see text. This spectrum was taken with a bias of 47 channels.

Figure 3 shows the highest energy gamma ray that we associated with N^{16}; its energy is 387 ± 5 kev.[8] This is the ground-state transition from the third excited state and its energy accords well with the value 391 ± 12 kev for the energy of the level derived from the particle measurements.[2] The rapid rise towards high channel numbers seen in Fig. 3 is due to the low-energy tail of an intense gamma ray of 490 kev which comes from the first excited state of F^{17} made by $O^{16}(d,n)F^{17}$ from O^{16} impurity in the N^{15}.

We now return to the problem of the possible gamma ray of 170 kev seen in Fig. 1. Since, as we shall see, the presence of such a transition would be of far-reaching consequence for the comparison with the shell-model calculation, it has been investigated in detail.

The experimental pulse distribution could be due either to a real gamma ray of 160–170 kev or to some backscattering effect from the higher energy lines which are present in abundance. If it were due to scattering of a higher energy line it might be possible, if the scattering took place outside the immediate target assembly, to modify it by placing scattering masses in the neighborhood. This was tried in many ways and, although changes in the pulse spectrum were of course produced, it could never be said that the appearance of the bump at channel 16 had been radically affected. This then suggested either that there was a real gamma ray of 160–170 kev or that it was due to scattering in the target assembly or the detector assembly. This latter possibility was next investigated by measuring the absorption of the various gamma rays in lead. If the scattering were in the detector assembly, then the absorption coefficient of the 165-kev bump would be appropriate to a gamma ray of higher energy; if the scattering were in the target assembly or if we were dealing with a real gamma ray, the absorption would be that of radiation of about 165 kev. For the reasons given, it was not possible to pull back the detector system far from the target and measure the absorption coefficients in good geometry. Instead the whole assembly was left as already described and a 180° lead absorber of superficial density 1.2 g/cm^2 was slipped into close contact with the gas target and between it and the crystal. The effect of the absorption on the composite spectrum is shown in Fig. 4. The strong lines are now at channel numbers 3, $26\frac{1}{2}$, and $42\frac{1}{2}$ and show absorptions agreeing well with those calculated for the bad geometry used. The 165-kev bump which now appears around channel 9 in the spectrum without lead is seen to be strongly absorbed as it would be if it were due to radiation of that energy leaving the target assembly, and not weakly absorbed as it would be if it left the assembly as one of the higher energy lines which was later degraded. To test the scattering of gamma rays within the target assembly, tiny sources of Au^{198}

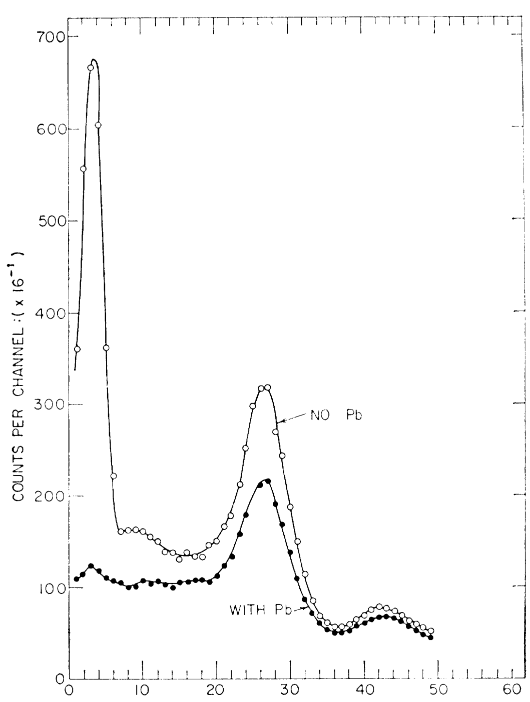

FIG. 4. Composite spectra showing the 118-, 275-, and 387-kev peaks at channels 3, $26\frac{1}{2}$, and $42\frac{1}{2}$ are shown with and without the presence of a lead absorber of superficial density 1.2 g/cm^2. The 160–170 kev bump seen around channel 9 without lead is strongly absorbed by the lead. These spectra were taken with a bias of 14 channels.

[8] Gamma rays from the present reaction are also reported by Hanna, Freeman, and Newton, *Proceedings of the 1956 Amsterdam Conference on Nuclear Reactions* (to be published). They report energies of 120, 275, and 390 kev in good agreement with the present measurements.

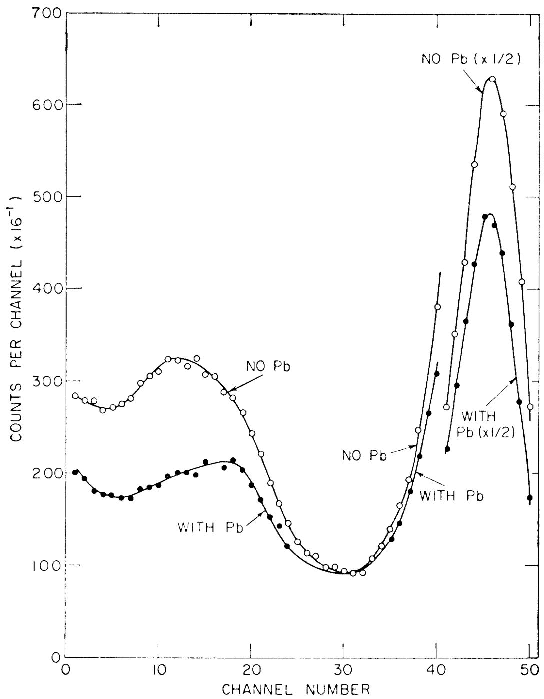

FIG. 5. Composite spectra with and without the same lead absorber used in Fig. 4, of the 411-kev radiation from Au^{198} from tiny sources situated within the gas-target tube. The strongly-absorbed peak seen at channel 12 has an energy of about 188 kev. The points on the spectrum with lead have not been shown between channels 25 and 34 to avoid confusion of the figure. These spectra were taken with a bias of 14 channels.

were placed inside the gas target and the 411-kev radiation was studied with and without the same lead absorber in exactly the same conditions as the experiment proper. The results are shown in Fig. 5. It is seen that the spectrum taken without the lead absorber indeed shows a strong peak at around channel number 12. This peak completely disappears with the interposition of the absorber and is replaced by the normal Compton edge around channel 18. The region of the pulse spectrum around the Compton edge shows the absorption characteristic of the 411-kev gamma ray[9] (compare with the absorption of the main photoelectric peak at channel 46), while the peak around channel 12 has shown the very much stronger absorption characteristic of a gamma ray of its own energy which is measured from the figure as 188 kev. This demonstrates then that backscattering does take place within the target assembly and gives rise to spurious peaks. Gamma rays of 411 kev backscattered through 180° have an energy of 157 kev, *viz.*, 31 kev lower in energy than the scattered peak of Fig. 5. This difference is due simply to the fact that gamma rays may scatter through any angle to reach the detector and so the peak is somewhat higher in energy than appropriate to the full backscattering. Full backscattering from the 275-kev radiation would give a gamma ray of 132 kev, and since the influence of the incomplete backscattering will be similar for both radiations we may anticipate a peak between 160 and 170 kev such as is observed. Furthermore, from the data of Fig. 5 we may compute the amount of backscattering to be expected from the 275-kev radiations and it agrees to within 20% with the amount of 160–170 kev radiation actually observed. We therefore think it extremely likely that the bump observed around 165 kev is not due to a gamma ray from N^{16} but to backscattering of the 275-kev radiation within the target assembly. For purposes of discussion we shall assume that any real line of 165 kev has a strength no greater than 30% of that appropriate to the full 165-kev bump.

COINCIDENCE MEASUREMENTS

The radiation at 275 kev could come from the ground state transition of the second excited state or from the cascade from the third through the first excited states or from both. To test the possibility of a cascade, coincidence measurements were made in which a second NaI(Tl) crystal was brought close to the target. Pulses in the original crystal which were in coincidence with pulses in the energy range 80 to 135 kev in this second crystal were displayed. It was immediately apparent that genuine coincidences were present but that their number fell far short of that to be expected if a substantial fraction of the 275-kev radiation were due to a cascade through a first excited state whose lifetime was shorter than the coincidence time used, namely 0.15

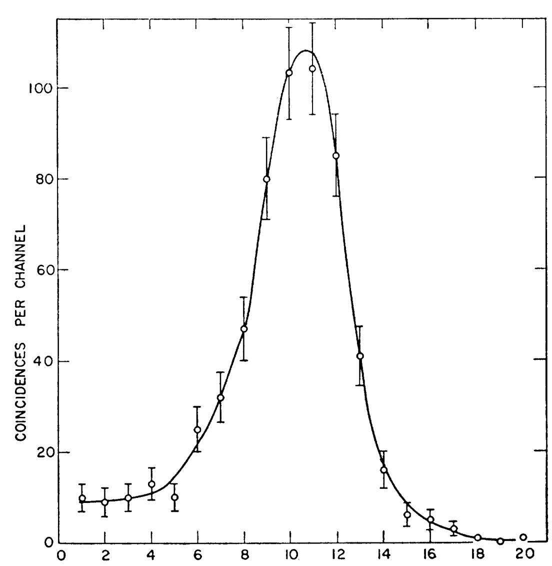

FIG. 6. Spectrum of the 268-kev line taken in coincidence with the 118-kev radiation on a delay of 0.2 microsecond. This spectrum was taken with a bias of 17 channels.

[9] We see from Fig. 5 that while the regions of the Compton edge and of the photoelectric peak show roughly the same absorption, the region of the trough around channel 30 seems to show no absorption at all. This is simply due to Compton scattering into this especially sensitive region of gamma-ray energy by the lead absorber of the primary 411-kev radiation.

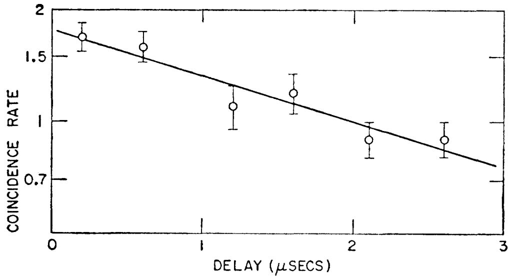

FIG. 7. Decay curve for the 118-kev radiation. The half-life indicated by this figure is (2.6±1.0) microseconds but this value is not to be relied upon heavily—see text.

microsecond. This sparsity of coincidences is in fact due to the long life of the 118-kev state. When no delay is used between the two crystals, the coincidence spectrum displays a peak at about 270 kev but there is a very large amount of low-energy pulses which almost fills up the trough below the peak and the ratio of the number of counts per channel in and above the peak is only about 2.5 to 1. When, however, a 0.2-microsecond delay is inserted in the high-energy or display leg of the coincidence circuit, a clean spectrum is obtained as is shown in Fig. 6. When the same 0.2-microsecond delay was inserted in the low-energy leg, coincidences dropped to a low and uniform level of about 3 per channel under the remaining conditions of Fig. 6. Many such coincidence spectra were measured and compared with the singles spectra obtained simply by relaxing the coincidence condition. In this way it was determined that the energy of the gamma ray in coincidence with the 118-kev gamma-ray is 7±3 kev less than the 275±4 kev measured for the radiations of Fig. 2 and so the energy of the cascade partner is 268±5 kev. This agrees exactly with the difference 269±6 kev between the gamma-ray energies of the ground state transitions from the first and third excited states. This then is our first suggestion that in fact the 275-kev radiation is a composite of gamma rays of slightly differing energy.

Coincidence spectra similar to that of Fig. 6 were taken over as wide a range of delay in the display leg as was available, namely 2.6 microsecond. From these results, a decay curve was constructed and is shown in Fig. 7. The half-life indicated by these results is 2.6±1.0 microseconds. However, the measurements were difficult to correlate with one another, owing to monitoring difficulties that in turn came from the very small deuteron currents that were used, and this lifetime measurement should not be relied upon. Figure 7 should rather be used to demonstrate that the first excited state is long-lived in the region of several microseconds. Another even rougher estimate of the lifetime was obtained from the absolute coincidence rate and was 10 microseconds. These two estimates are certainly consistent with each other.

INTENSITIES AND THE DECAY SCHEME

The intensities of the three strong lines were determined as 96±10, 150±15, and 26±5 for the 118-, 275-, and 387-kev radiations, respectively, in arbitrary units. Although the intensities were estimated for a single position of the detector, they must be fairly good estimates of the total intensities since the detector was large and close to the extended source and centered on $\theta=90°$. It is at once sure that the 275-kev radiation must be composite since there is more of it than of 118 kev. To determine the decay scheme in more detail, we made use of the stripping results[5] in the manner discussed above. These results show that under our conditions the three excited states are initially populated with intensities 1, 1.7±0.1 and 3.4±0.2 in ascending order of energy. A set of gamma-ray intensities consistent with these various pieces of information is shown in Fig. 8. The limit on the intensity of the cascade from the second excited state is obtained in the manner already discussed. That on the intensity of the transition between the third and second excited states comes from the coincidence measurements. If this cascade were present, the upper member would have an energy of 102 kev and so fall in the coincidence channel. The following 285-kev gamma ray which would be presumably in prompt coincidence (see later) would then appear when there was no delay in the display leg and disappear when the delay was inserted. In fact, no increase in the intensity of the coincidence peak was

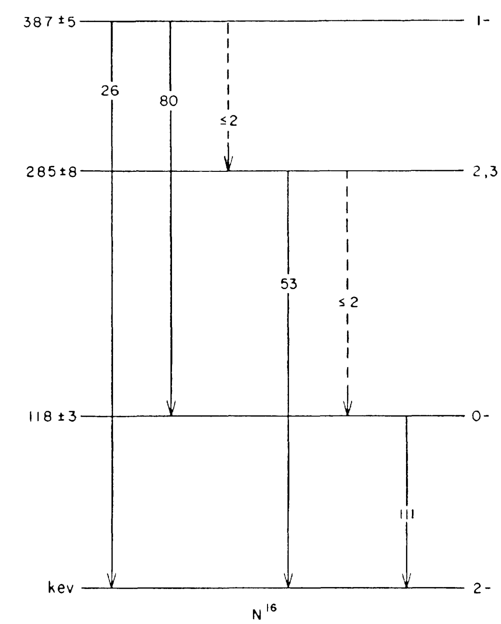

FIG. 8. Decay scheme and proposed spin assignments for N^{16}. The energies of the levels are those derived in the present work. The numbers on the transitions are the relative intensities in arbitrary units when the levels are excited in the reaction $N^{15}(d,p)N^{16}$ by using deuterons of from 2.6 to 2.9 Mev. They have been derived from the present investigation and by comparing it with work on the protons themselves in the same reactions under the same conditions.

detected when there was no delay in the display leg. The long life of the 118-kev state makes this an especially sensitive test for the alternative cascade (a half-life as indicated by Fig. 7 was used for working out the limit on the abundance shown in Fig. 8).

The energy shown for the second excited state in Fig. 8 is derived from the energy of the cascade contribution to the 275 ± 4 kev radiation, namely 269 ± 6 kev, and from the relative intensities of the cascade radiation and the ground-state transition from the second excited state derived as explained above by comparing the gamma-ray and proton results. Our figure of 285 ± 8 kev is in fair accord with the energy 300 ± 12 kev derived from the particle work.[2]

SPIN ASSIGNMENTS

The stripping results[5] allow spins 0 to 1 for the first excited state. The long lifetime makes $J=0$ very probable because a mean life as short as 3 microseconds for this state would imply $|M|^2=7\times10^{-6}$ in Weisskopf units for the $M1$ transition if in fact $J=1$. In fact, the mean life is probably quite a bit longer than this and so $|M|^2$ is even smaller. So small a value of $|M|^2$ is unconscionable. On the other hand, the $J=0$ assignment leads to $|M|^2=1.7$ for the $E2$ transition for the half-life of Fig. 7 and this is very reasonable. (The correction due to internal conversion is negligible.)

$J=0$ for the first excited state fixes the spin of the third excited state as $J=1$ since the stripping results allow 0 or 1 but the observed cascade eliminates the possibility $J=0$.

We have already remarked that, of the possibilities $J=1$, 2, or 3 that the stripping results allow for the second excited state, $J=1$ is not very likely. This is reinforced by the absence or weakness of the cascade from this state through the $J=0$ state as found in our work. The stripping and gamma-ray results then both suggest $J=2$ or 3 although even in conjunction they cannot eliminate $J=1$ completely. Similarly the weakness of the transition between the third and second excited state argues, though only very weakly, in favor of $J=3$ rather than $J=2$ for the second excited state. In our analysis of the coincidence work, we have presumed that the second excited state is short-lived compared with 0.15 microsecond. This is extremely likely for any of the three choices of spin allowed by the stripping results since an $M1$ transition to the $2-$ ground state would always be possible.

COMPARISON WITH THEORY

The theoretical prediction[1] that these four states should be $J=0$, 1, 2, and 3 and of odd parity seems very well borne out. The choice $J=0$, 1, and 2 with odd parity seems fairly sure for three of the four while the experimental preference for $J=3$ or 2 with odd parity for the remaining one is in agreement with the remaining theoretical assignment of $J=3$. We might here notice the great importance of the 165-kev bump on which we dwelt in detail: had it represented a real gamma ray, then $J=3$ would have been impossible for the second excited state and the theoretical model would have faced a severe contradiction. It is desirable that this point should be returned to if cleaner experimental conditions can be obtained. In particular, a repetition of the present work using proportional counters instead of scintillation counters should enable, by virtue of the greater resolution, an easier discrimination between a true gamma-ray line and backscattered radiation to be made. On the theoretical side it will be interesting to see whether an account is given of the branching of the third excited state which favors the cascade over the ground-state transition. A better measurement of the lifetime of the first excited state will also be interesting since, if the present figure should be correct, it seems that this $E2$ transition may be a little enhanced over single-particle speed and the shell model clearly cannot account for such an enhancement in this case. The situation may then be similar to the familiar case of the second excited state of F^{19}.

COMPARISON WITH O^{16}

It is probable that the first $T=1$ state of O^{16} is the $2-$ state at 12.95 Mev[10]; the next $T=1$ state is $1-$ and is at 13.09 Mev.[10] This spacing of only 140 kev as compared with the 387 kev for the corresponding spacing in N^{16} is probably due to a large Thomas shift for the upper O^{16} level which is 150 kev wide and has a very large reduced width for s-wave proton emission to the ground state of N^{15}. Also the partial breakdown of isotopic spin in this region of O^{16} will result in certain level displacements.[10]

ACKNOWLEDGMENTS

I should like to thank Dr. S. D. Bloom who participated in the early stages of this investigation and also Mr. A. G. Rubin who was of great assistance in making the measurements.

[10] D. H. Wilkinson, Phil. Mag. 1, 379 (1956).