Decay Schemes of C^{15}, N^{16}, and O^{19}†

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An iron-free intermediate-image spectrometer has been used to measure the beta-ray spectra of 2.25-sec C^{15}, 7.4-sec N^{16}, and 29-sec O^{19} and to measure the positron-electron internal pair conversion lines occurring in C^{15} and N^{16} decays. C^{15} emits a beta-ray branch of end-point energy 9.82±0.04 Mev to the $\frac{1}{2}-$ ground state of N^{15} and a branch of 4.51±0.03-Mev end-point energy. Relative intensities are (32±2)% (log ft=6.0) and 68% (log ft =4.1), respectively, and both components have the allowed shape. From pair line measurements at 1.5% resolution the C^{15} gamma-ray energy is 5.299±0.006 Mev, and thus the inner beta-ray group leads to the upper member of the (5.276−5.305)-Mev doublet level in N^{15} known from the $N^{14}(d,p)N^{15}$ reaction. The internal pair conversion coefficient derived for the 5.299-Mev line agrees best with an *E1* assignment. Our data require spin and parity $\frac{1}{2}+$ or $\frac{3}{2}+$ for the 5.305-Mev level in N^{15}, and spin and parity $\frac{1}{2}+$ or $\frac{3}{2}+$ for C^{15}. Taken together with other evidence it seems likely that both states are $\frac{1}{2}+$. No evidence could be found from gamma-ray measurements for the beta decay of C^{15} to other known states of N^{15}. Some comments are made on the intermediate-coupling model for $A=15$. In the decay of N^{16} we find that the 3.3-Mev beta-ray branch to the 7.11-Mev level in O^{16} is <11% per decay, based on the Kurie-plot analysis. A value of (4.7±0.9)% per decay for this branch is derived from the intensity of the 7.11-Mev pair line. O^{19} decays with beta-ray branches of 4.601 ±0.015 Mev [(41.5_{-5}^{+2})%, log ft=5.4] and 3.25±0.02 Mev (58.5%, log ft=4.5). Other results include a value of 5.416 ±0.015 Mev for the beta-ray end-point energy of F^{20} and a value of 6.051±0.005 Mev for the energy of the pair-emitting state of O^{16}.

INTRODUCTION

Two of the light element beta-ray emitters which have not been studied hitherto by means of magnetic spectrometer techniques are C^{15} and O^{19}. C^{15} (half-life 2.25 sec) is reported[1] to decay 20% to the ground state of N^{15} with an end-point energy of 9.5±0.3 Mev, while the remaining beta rays lead to the (5.276–5.305)-Mev doublet in N^{15} followed by gamma radiation. The C^{15}–N^{15} mass difference calculated from nuclear reaction Q values[1] is 9.78±0.01 Mev. We have studied C^{15} with the following aims: to determine the shapes, branching ratios, and end points of the two beta-ray components; to establish to which member of the 5.3-Mev doublet the inner beta-ray group decays; to find the multipole order of the gamma radiation; to fix the spin and parity of C^{15} from the various measurements; and to search for gamma rays which would indicate beta-ray branching to other known states in N^{15}.

O^{19} (half-life 29 sec) has been reported[1] to decay with a beta-ray branch of 4.5±0.3 Mev (30±10)% to the 0.198-Mev state in F^{19} and a branch of 2.9±0.3 Mev (70%) to the 1.56-Mev state. We undertook an investigation of the beta-ray spectrum in order to determine more accurate branching ratios and to look for a possible branch to the ground state of F^{19}.

During the course of the C^{15} work we used N^{16} as a comparison beta-ray activity. Owing to a discrepancy[2] between previously reported gamma-ray intensities and the beta-ray branching intensity to the 7.11-Mev level in O^{16}, derived from Kurie-plot analyses, we have made a study of the inner beta-ray group and have also detected and measured the intensity of the 7.11-Mev pair line.

EXPERIMENTAL METHODS

C^{15} activity was made by the $C^{14}(d,p)C^{15}$ reaction using deuterons of 2.8 Mev from the Van de Graaff accelerator. The target had been prepared by J. N. McGruer at the University of Pittsburgh and was kindly placed at our disposal. It consisted of a layer of carbon 1.2 mg/cm² in thickness containing 30% C^{14} deposited on a gold backing 0.2 mg/cm² thick. This was cemented at its edges onto a water-cooled holder at the normal source position of the spectrometer. The O^{19} activity was made in the $O^{18}(d,p)O^{19}$ reaction at E_d =2.8 Mev. Targets were prepared from water enriched to 22% O^{18} obtained from the Weizmann Institute in Israel, by anodizing one side of a 7 mg/cm² thick tantalum foil. The thickness of the tantalum oxide layer was estimated to be ~0.7 mg/cm² thick from the color changes occurring during the anodizing process. Nitrogen enriched to 95.6% N^{15} was used for making N^{16} by the $N^{15}(d,p)N^{16}$ reaction. The samples consisted[2] of a layer of TiN powder a few mg/cm² thick cemented onto a 0.0005-in.-thick nickel foil. A CaF_2 target 1 mg/cm² thick, vacuum evaporated onto a nickel foil, was also used in some of the work. In all cases the target was on the spectrometer side of the backing such that the beam passed through the backing, then through the target and on to the beam-collecting cup.[2] For scintillation spectrometer measurements the C^{14} or TiN^{15} samples were cemented onto the bottom of a $\frac{3}{4}$-inch diameter cylindrical brass target cup located at the end of the beam pipe.

The iron-free intermediate-image beta-ray spectrometer[3,2] was operated with two different detecting sys-

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[1] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. 11, 1 (1959).
[2] D. E. Alburger, Phys. Rev. 111, 1586 (1958).
[3] D. E. Alburger, Rev. Sci. Instr. 27, 991 (1956).

tems. For measuring positron-electron internal pair conversion lines the arrangement was the same as that described earlier,[2] whereas when beta-ray spectra were investigated the pair coincidence detector was replaced with a Geiger-Müller counter having a 3 mg/cm^2 thick window.

Owing to the high energies of the beta rays to be studied, the previous upper limit of 9 Mev in the focusing energy of the spectrometer had to be raised. This was accomplished by making a series connection of the two generators in the three-unit M-G set in place of the former parallel connection. Proper current regulation was achieved at a maximum of 855 amperes and 150 volts (128 kw) which focuses electrons of 11 Mev. Under steady-state conditions at 128 kw and with the full water-cooling pressure, the inlet and outlet water temperatures were 10°C and 77°C, respectively.

In the measurement of the various beta-ray spectra two methods of normalizing the data were employed. The C^{15} and N^{16} beta-ray spectra were normalized on the high-energy gamma rays which were detected in a 2×2 inch NaI crystal located just outside the vacuum chamber and next to the magnetic field coil at the source end, a point which is 12 inches from the target. A 4-foot-long light pipe extending perpendicularly to the spectrometer axis connected the crystal optically to an RCA-6342 photomultiplier tube surrounded by four coaxial iron magnetic shields. With this arrangement the pulse-height resolution was adequate for our purposes and no influence of the spectrometer magnetic field on the phototube gain could be observed at the maximum coil current. When the bias on the gamma-ray monitor was adjusted so as to detect pulses of >3 Mev, the background was only a few percent of the total yield of C^{15} or N^{16} gamma-ray counts. However, this method was not very suitable for the F^{20} study, since the background was $\sim 10\%$, and it failed completely with O^{19} because of a relative background of $\sim 50\%$ which varied with time. In the latter two cases the gamma rays have energies of 1.63 and 1.35 Mev, respectively, and it is not possible to bias out the activities induced in the crystal and elsewhere by neutrons.

At the suggestion of Ralph Pixley we used the leaky integrator method[4] of monitoring the F^{20} and O^{19} activities. This technique consists of connecting the beam-collecting cup to one side of a parallel *RC* circuit (the other side being at ground potential) whose time constant is the same as the mean life of the activity being studied. Precautions were taken to avoid leakage currents and we employed plastic film capacitors of 1–5 mf (Plasticon, made by Condenser Products Company, Chicago). With initial conditions of no activity and zero voltage across the circuit the dc voltage developed by the beam is proportional to the amount of activity of the corresponding mean life in the target provided (a) the beam energy is constant, (b) the target is uniform, and (c) the beam reading is not affected by varying secondary electron emission effects. In the geometry of the spectrometer (see reference 2, Fig. 2), the secondary electrons from both the target and the beam cup are confined by the magnetic field to move nearly parallel to the axis. By placing the cup and the target each at a bias of +45 v, we expected that there would be enough of a potential barrier in the region between the target and the cup so as to restrict much of the intermingling of their respective secondary electrons. Measurements on the known F^{20} beta-ray spectrum, which will be discussed later, resulted in a good spectrum shape and showed that if any secondary electron mixing occurs it is not strongly magnetic-field dependent when the biases are imposed. The procedure was to bombard the target until the voltage across the *RC* integrating circuit, as read on a type 1800-*A* General Radio vacuum-tube voltmeter, passed a given reference point at which time the Van de Graaff beam was cut off. The reference voltage was 0.3–1.2 volts in the various runs. Just as the meter voltage dropped past the reference point, the scalars were turned on for a fixed timing interval. Successive runs at one point on a beta spectrum established whether the time constant of the *RC* circuit was adjusted accurately.

When taking positron-electron internal pair conversion data on C^{15} and N^{16}, the singles counting rate from one of the pair-detecting crystals, resulting from focused beta rays, was used for monitoring. The variation of this rate is negligible over the small momentum interval of a coincidence pair line.

In studies of the F^{20} and O^{19} beta-ray spectra the beam was removed by turning off the Van de Graaff belt excitation. However, when the pair lines of C^{15} and N^{16} were examined it was found desirable, because of the short half-lives and the long runs necessary, to use the automatically operated beam interceptor.[2] The cam system previously used for N^{16} was employed again and for C^{15} the frequency of the timing cycle was doubled so as to result in irradiation and counting intervals of approximately 3 sec each.

All data on beta-ray spectra were taken at a spectrometer resolution setting of 1.6% using a 3-mm

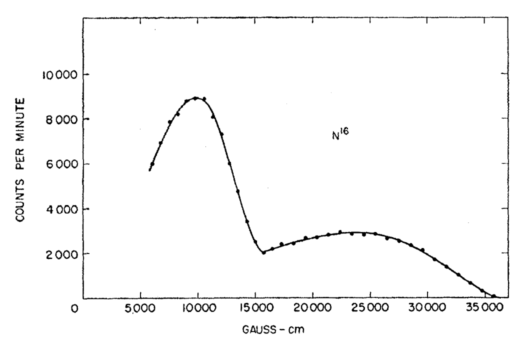

FIG. 1. Beta-ray spectrum of N^{16}.

[4] S. C. Snowden, Phys. Rev. 78, 299 (1950).

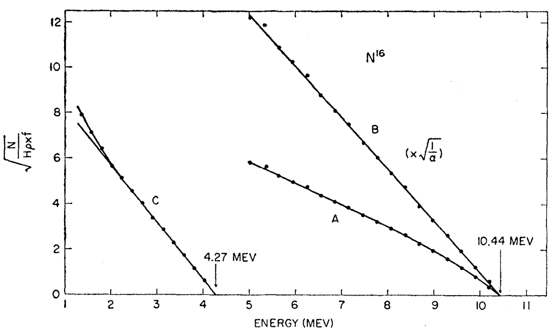

FIG. 2. Kurie-plot analysis of the N^{16} beta-ray spectrum. Curve A, ordinary Kurie plot of the high-energy group; Curve B, correction of curve A with the "unique" first-forbidden factor α; and Curve C, Kurie plot of the inner group after subtraction of the α-shaped high-energy spectrum. Note: the three plots are made with different ordinate scales.

diameter beam spot for activating the target. Positron-electron pair lines were measured at 1.5% resolution. In all cases the calibration was taken from the 9986.7 $\pm$1.5 gauss-cm line[5] of thorium-active-deposit, the source having been collected electrostatically on a 3-mm diameter Al foil. The linearity of current *versus* momentum was checked occasionally with the 4657.9$\pm$1.0 gauss-cm line[5] of Bi^{207}. Calibrations were generally made before and after the various runs and the voltage across the reference potentiometer in the current regulating circuit was monitored frequently. Care was taken to adjust the axial positions to be nearly the same for both the target and the calibration source, and small corrections[3] were applied to the calibration constant when required by slight differences in axial position.

When our initial runs were made on the O^{19} beta-ray spectrum, we found that a considerable amount of 66-sec F^{17} was present. In order to prevent the detection of the positrons from this activity ($E_{\max}=1.75$ Mev), we installed a spiral baffle system which has been described earlier.[6]

BETA-RAY SPECTRA

The study of the N^{16} beta-ray spectrum was made in order to check the operation of the spectrometer at high focusing energies and to investigate the shape of the inner group as mentioned in the Introduction. Figure 1 shows the spectrum obtained. Data were corrected for counter dead-time, normalized according to the accumulated gamma-ray monitor count, and the background averaged from points beyond the end of the spectrum has been subtracted out. A Kurie-plot analysis of the spectrum is shown in Fig. 2. Curve A, the normal Kurie plot of the high-energy group, shows the distinct curvature previously observed by Morton and Lewis[7] and by Brunhart, Kenney, and Kern.[8] When this plot is corrected by means of the unique first-forbidden factor α, a linear plot, Curve B, is obtained having an extrapolated end-point energy of 10.44$\pm$0.04 Mev. This energy is in agreement with the previous measurements and with the value 10.40$\pm$0.01 Mev calculated from reaction Q values.[1] After subtraction of the high-energy α-shaped group from the total spectrum the Kurie plot of the remainder is found, as shown by Curve C. The points of this plot are quite linear from 2 Mev to the end point at 4.27$\pm$0.03 Mev, and there is no evidence of a deviation starting at 3.3 Mev as has been found before.[7,8] This end point is to be compared with 4.27$\pm$0.02 Mev expected for a transition to the 6.14-Mev state of O^{16}. In order to determine the intensity of 3.3-Mev beta rays which would be required to produce a noticeable departure from linearity above 2 Mev in Curve C, we constructed Kurie plots from combined 4.3- and 3.3-Mev end-point beta-ray spectra of allowed shapes having various relative intensities. An intensity ratio $I_{3.3}/I_{4.3}=1/10$ produces a noticeable curvature above 2 Mev and we consider the ratio 1/7 to be a firm upper limit. This corresponds to an upper limit of 11% per decay on the 3.3-Mev branch. Deviations in the earlier Kurie plots[7,8] at 3.3 Mev probably resulted from source thickness effects. From the areas under the total spectrum and under the extrapolated high-energy group we find that the intensity per decay of the ground-state group is (26$\pm$2)%. This is the same as the mean value of the two previous results of 24%[7] and 28%.[8]

The beta-ray spectrum of C^{15} is shown in Fig. 3 and the corresponding Kurie-plot analysis is given in Fig. 4. Data were taken and analyzed in a manner similar to the case of N^{16}. It is seen that the high-energy group has the allowed shape, extrapolating to an energy of 9.82$\pm$0.04 Mev, and that the inner group is also allowed, extrapolating to an energy of 4.51$\pm$0.03 Mev. The intensities per decay are (32$\pm$2)% for the 9.82-Mev group and 68% for the 4.51-Mev group. Reaction Q values predict an end-point energy of 9.78$\pm$0.01 Mev

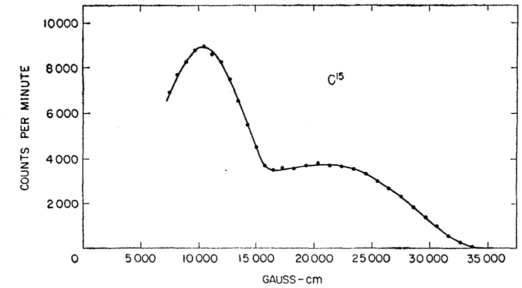

FIG. 3. Beta-ray spectrum of C^{15}.

[5] K. Siegbahn, *Beta- and Gamma-Ray Spectroscopy* (North-Holland Publishing Company, Amsterdam, 1955), see p. 227.

[6] Alburger, Ofer, and Goldhaber, Phys. Rev. **112**, 1998 (1958).

[7] P. W. Morton and H. W. Lewis, Bull. Am. Phys. Soc. **2**, 286 (1957).

[8] Brunhart, Kenney, and Kern, Phys. Rev. **110**, 924 (1958); Bull. Am. Phys. Soc. **2**, 395 (1957).

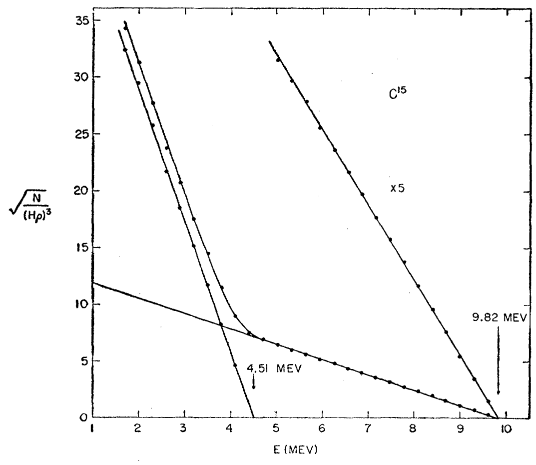

FIG. 4. Kurie-plot analysis of the C^{15} beta-ray spectrum.

for C^{15}. These data indicate that the inner group leads to a state in N^{15} at 5.31 ± 0.05 Mev which is to be compared with states known at 5.276 ± 0.006 and 5.305 ± 0.006 Mev.[1]

The F^{20} beta-ray spectrum was run primarily to test the leaky integrator monitoring technique in connection with the O^{19} spectrum. The 10% background in the gamma-ray monitor, while bothersome, was low enough so that the integrator normalization could be checked against the gamma-ray monitor. When the leaky integrator was used alone, a spectrum was obtained which has a linear Kurie plot between 2.0 Mev and the 5.4-Mev end point. Runs were made on the F^{20} spectrum above 3.5 Mev in order to obtain end-point energy values which could serve as a test of the reliability of the leaky integrator monitoring method. An F^{20} end-point energy of 5.416 ± 0.015 Mev was obtained, this being the average from analyses based on integrator monitoring and on gamma-ray monitoring. The separate results on the end point using the two monitoring techniques differed by 0.008 Mev. If the gamma ray in F^{20} decay is taken as 1.629 Mev, which is the mean of two reported measurements,[1] the adjusted mass values published by Wapstra[9] predict a beta-ray end-point energy of 5.420 ± 0.013 Mev, where 0.001 Mev associated with nuclear recoil has been subtracted.

In Figs. 5 and 6 we show the O^{19} beta-ray spectrum and its Kurie-plot analysis, respectively. The higher-energy group appears to have the allowed shape. Its end-point energy of 4.601 ± 0.015 Mev was derived from the analysis of a series of runs with closely spaced points in the region above 3.3 Mev. Upon extrapolating the Kurie plot of the 4.6-Mev group, its calculated spectrum was subtracted from the total leaving the inner group whose Kurie plot is linear above 1.8 Mev and has an end-point energy of 3.25 ± 0.02 Mev. Relative branching intensities are $(41.5_{-5}^{+2})\%$ (log $ft=5.4$) for the 4.601-Mev group (see the Discussion section for an explanation of the errors in the branching intensity) and 58.5% (log $ft=4.6$) for the 3.25-Mev branch. These data are consistent with the known decay scheme[10] of O^{19}.

POSITRON-ELECTRON PAIR LINE MEASUREMENTS

Because the separation of the 5.3-Mev doublet levels in N^{15} is only 0.029 Mev, or 0.55%, a measurement of the transition energy with an accuracy of $\sim 0.1\%$ is necessary in order to establish to which of these levels C^{15} decays. The beta-ray measurements reported above favor the upper level but the errors are not small enough to establish which level is involved. As a check on our experimental accuracy, we carried out a series of measurements on the pair-emitting first excited state of O^{16} produced in the $F^{19}(p,\alpha)O^{16}$ reaction. A previous pair-line measurement[3] yielded an energy of 6.065 ± 0.009 Mev, but according to more recently determined reaction Q values[1] the weighted energy is 6.053 ± 0.007 Mev. Our procedure was to make alternate comparisons at 1.5% resolution between the peak position of the pair line and that of the thorium calibration line, the momentum[5] of which differs by only 0.4% from the momentum of the pair line. A correction of 0.03% was made for a difference of 0.1 mm in the axial position of the target relative to that of the thorium source. This difference was determined by inserting, in turn, the source-holding tube and the target-holding tube in a bench-mounted jig and by locating the axial position of the surface of the source or target relative to a reference point by means of a depth micrometer. Corrections were also made for energy loss due to the 1.0-mg/cm^2 thickness of the CaF_2 target and for the nuclear recoil associated with the emission of a pair. No Doppler correction is necessary owing to the long half-life of the state (7×10^{-11} sec). According to these measurements the energy of the pair-emitting state is 6.051 ± 0.005 Mev. We propose that the earlier pair-line energy[3] be replaced by the present one and that this result be combined with the reaction Q-value figure

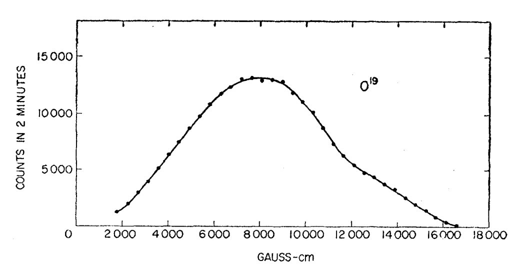

FIG. 5. Beta-ray spectrum of O^{19}.

[9] A. H. Wapstra, Physica **21**, 367 (1955).

[10] Johnson, Jones, Phillips, and Wilkinson [Proc. Roy. Soc. (London) (to be published)] give a high-energy branch of 38.5% from observations on the gamma rays following the beta decay of O^{19}. See also Jones, Phillips, Johnson, and Wilkinson, Phys. Rev. **96**, 547 (1954).

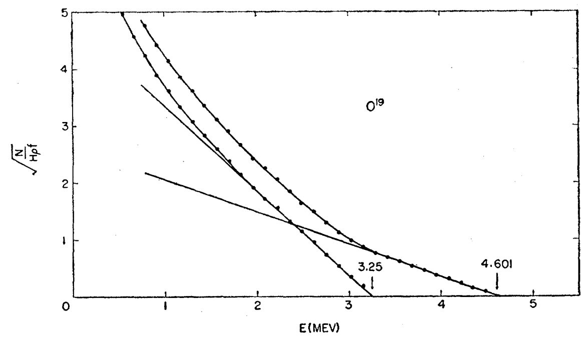

FIG. 6. Kurie-plot analysis of the O^{19} beta-ray spectrum.

mentioned above to give a most probable energy value of 6.052 ± 0.004 Mev for the first excited state of O^{16}.

The energy of the C^{15} gamma ray was measured in a manner similar to that described above, except that the pairs occurring in the decay were detected only during the "beam-off" portion of the cam timing cycle just as in earlier work[2] on N^{16}. Figure 7 shows the results of one 15-hour run on the pair coincidence line. We derive an energy value of 5.299 ± 0.006 Mev for the gamma-ray transition in N^{15} based on two such runs which separately gave the energy as 5.298 and 5.300 Mev. The relative predicted positions of the peaks for gamma rays of 5.276 and 5.305 Mev, with their errors, are also shown in Fig. 7 and it is seen that our measurement agrees better with the position of the 5.305-Mev level. A 5.276-Mev transition may also be present but its intensity must be $<\frac{1}{3}$ of the total gamma-ray intensity. An accurate experimental re-check on the energies of these levels from the $N^{14}(d,p)N^{15}$ reaction would be desirable.

In order to fix the multipolarity of the 5.3-Mev transition, we made comparisons between the number of pair counts per gamma ray for this line and for the 6.14-Mev $E3$ transition in O^{16} following the decay of N^{16}. Our procedure was to determine the net number of pair counts at the peak of the line per standard monitor count of 100 000 counts recorded in one of the crystals. The singles monitoring yield results almost entirely from focused beta rays. Owing to the differences in shapes and end-point energies of the C^{15} and N^{16} beta-ray spectra and to the different relative momentum positions of the pair line with respect to the beta-ray spectrum, the 100 000 monitor counts corresponds to different total numbers of disintegrations. This difference of approximately 10% was determined from an analysis of the amplitudes of the beta-ray spectra at the pair-line positions together with the areas under these spectra. The observed ratio of pair-line intensities was thus reduced to a ratio of intensities for equal numbers of beta-ray disintegrations. Generally one would then apply a factor, according to the relative branching intensities, to derive the ratio of pairs for equal numbers of gamma-ray transitions. However, in our case, it happens that both branches to the gamma-emitting level are 68% and no further correction is necessary.

From the ratio of pair counts for equal numbers of gamma-ray transitions, a derivation of unknown internal pair conversion coefficient of the 5.3-Mev gamma ray in C^{15} decay, based on the theoretical coefficient for the 6.14-Mev $E3$ gamma ray in N^{16} decay, would be straightforward if it were not for the fact that the pair transmission of the spectrometer (defined as the number of coincidence counts at the peak of a line per *pair* emitted from the source) varies both with energy and with multipole order owing to differences in angular correlations of the pairs. In earlier work[2] it was found experimentally that the spectrometer is 1.5 times more efficient in detecting 6.14-Mev $E3$ pairs than it is in detecting 6.05-Mev $E0$ pairs. Since in the analysis one must make use of the relative pair transmissions, it would appear that the pair conversion coefficient could be derived only if the multipole order of the transition in question is already known.

We believe that the correct procedure is to assume a number of different multipole orders for the unknown transition, to make use of the spectrometer transmission appropriate to each assumption, to derive the various internal pair conversion coefficients, and to compare these with the theoretical values for the assumed multipoles. A unique assignment may be made if a derived coefficient agrees with its corresponding theoretical coefficient in one case only. An inherent combination of characteristics limits this comparison method, namely

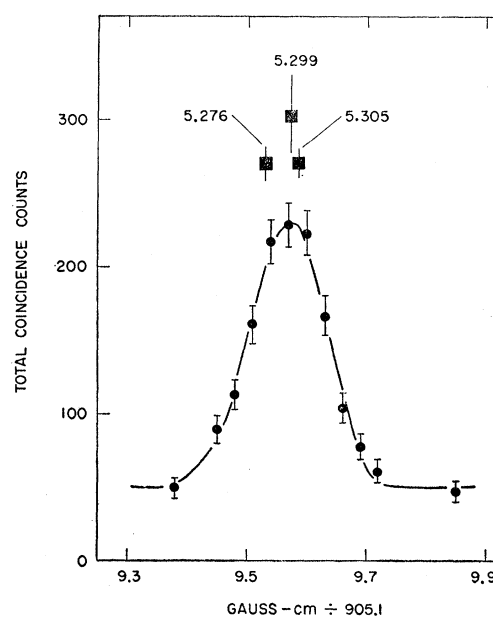

FIG. 7. Internal pair conversion line occurring in the decay of C^{15}. The full width at half maximum is 1.5%. Predicted peak positions are shown for the 5.3-Mev doublet levels in N^{15} known from the $N^{14}(d,p)N^{15}$ reaction.

that, in general, the higher the multipole order the greater will be the spectrometer transmission because of angular correlation effects—but the effect of this greater transmission on the pair-line yield tends to be cancelled by the fact that the higher the multipole order the lower will be the internal pair conversion coefficient.[11] In order to make a unique multipole order assignment, the accuracy of the measurements must be greater than would obtain if the spectrometer pair transmission were independent of multipole order.

With the help of Ralph Pixley we calculated the pair transmission of the spectrometer as a function of multipole order and transition energy with an accuracy which is limited only by the lack of exactness with which the mean entrance angle and the acceptance angle of the spectrometer are known. Pairs of equal energy are chosen, one component of which is allowed to enter the acceptance angle. The probability that the other component will also enter is found by integrating the angular correlation function[11] over the acceptance angle geometry. This probability is multiplied by the solid angle for the passage of the first particle and by a resolution-dependent energy-width factor, which represents the fraction of the pair spectrum accepted, thus giving the total probability that both components shall reach the detecting area. It is assumed that the points where the pairs enter the detecting area are uncorrelated, in which case just half of the pairs produce coincidence counts except for a loss of 5% due to the interception of pairs by the tungsten absorber between the crystals. Further corrections to the experimental coincidence yields must be made for the number of counts lost, because of the pulse-height bias conditions on the detectors.

We have, up to the present, several experimental checks on the calculations. The experimentally observed absolute pair transmission for the 6.14-Mev $E3$ transition in O^{16} following N^{16} decay differs from the calculated transmission by only 10% which is within the experimental accuracy. Our other checks are on the ratios of pair transmissions. As mentioned earlier, we had previously[2] measured the ratio of 6.14-Mev $E3$ to 6.05-Mev $E0$ transmission as 1.5 (with an accuracy of ~10%). The theoretical ratio is 1.45. Furthermore, the calculations show that the ratios of transmissions should not vary appreciably over the entire range of spectrometer resolution settings, and experimentally this has been found[2] to be true for the two transitions mentioned above. Finally, we were able to detect and measure the intensity of the internal pair conversion line of the 7.11-Mev $E1$ transition occuring in the decay of N^{16} and to derive from the data a beta-ray branching ratio which is in agreement with the known decay scheme.

The measurement of the 7.11-Mev pair-line intensity in N^{16} decay was difficult because of the small peak yield relative to the background. The background arises both from random counts and from true coincidences between the continum of beta rays and that of 6.14-Mev pairs. Our procedure was to focus alternately at the pair-line peak position and at background points on either side of the line. 3471 peak counts and 2959 background counts (both for the same accumulated monitor count) were the totals for 40 sets of points obtained in a 16-hour run. We derive the relative 7.11-Mev gamma-ray intensity from the pair-line intensity by using the 6.14-Mev pair-line intensity as a reference, together with the theoretical internal pair conversion coefficients and our calculated relative spectrometer transmissions. In this case the ratio of calculated transmissions is $(7.11\ E1)/(6.14\ E3)=1.185/1.444$ (based on a transmission of 1.000 for $E0$). The yields must be adjusted for the slightly different numbers of monitor counts per beta ray. We find that the relative 7.11-Mev gamma-ray intensity, and therefore the intensity of the 3.3-Mev beta-ray branch of N^{16} to this state in O^{16} is $(4.7\pm0.9)\%$ if we take the 4.3-Mev beta-ray branch as 68%. This result is in excellent agreement with the $(4.9\pm0.4)\%$ branch[2] based on gamma-ray intensities. If, on the other hand, we assume that the gamma-ray intensities are correct, the result confirms our spectrometer transmission calculations for $E1$, at least within an accuracy of 19%. In none of our experimental checks on the spectrometer pair transmission do we feel that the measurements establish the transmission characteristics to the accuracy with which we believe the calculated transmissions.

Returning to the C^{15} gamma ray, we find from our comparison measurements that the yield of C^{15} pair coincidence counts per 5.3-Mev gamma ray is 1.11 times larger than the number of pair counts per 6.14-Mev gamma ray in N^{16} decay. The internal pair conversion coefficient α for the C^{15} gamma ray is given by the relationship:

$$\alpha_{C^{15}}=1.11(\epsilon_{N^{16}}/\epsilon_{C^{15}})\times1.46\times10^{-3},$$

where the ϵ's are the respective pair transmissions and the factor 1.46×10^{-3} is the theoretical internal pair conversion coefficient for the 6.14-Mev $E3$ transition in O^{16}.

In Table I we list the calculated relative spectrometer transmission for various multipoles (the numbers are based on a relative transmission of 1.000 for 6.05-Mev

TABLE I. Summary of calculations on the internal pair conversion coefficient α for the 5.3-Mev gamma ray in C^{15} decay.

Multipole	Relative spec. trans. (=1.000 for $E0$)	$\alpha\times10^3$ (exp) ($\pm10\%$)	$\alpha\times10^3$ (theor)	Δ in Nos. of prob. errors
$E1$	1.065	2.20	2.08	0.6
$M1$	1.280	1.83	1.38	2.5
$E2$	1.261	1.86	1.54	1.7
$M2$	1.423	1.64	1.12	3.2
$E3$	1.407	1.66	1.24	2.5

[11] M. E. Rose, Phys. Rev. **76**, 678 (1949).

$E0$ pairs—for $E0$ the transmission changes very little with energy), the corresponding experimental internal pair conversion coefficient, and the theoretical coefficient. The last column gives the difference Δ between experimental and theoretical values in numbers of probable errors of the experimental number. Only in the case of $E1$ do the experimental and theoretical values agree within the probable error of the experimental result. Experimental values for all other multipoles, with the possible exception of $E2$, are well outside the probable errors and we feel that the results fix the 5.3-Mev transition with reasonable certainty as $E1$. The exclusion of $E2$ is strengthened by theoretical considerations to be presented later.

SCINTILLATION SPECTROMETER MEASUREMENTS

States above 5.3 Mev are known[1] in N^{15} which energetically could be fed by beta decay from C^{15}. In particular, there are levels at 7.31 and 8.32 Mev both of which have spin and parity $\frac{1}{2}+$ or $\frac{3}{2}+$, and if our evidence that C^{15} has spin and parity $\frac{1}{2}+$ is correct, one might expect allowed beta-ray transitions to take place.

Two types of experiment were performed to search for such branching. In the first we looked for gamma rays of low energy in coincidence with the 5.3-Mev gamma ray. Two 3×3 inch NaI(Tl) detectors were placed on either side of the target with $\frac{1}{4}$ inch of iron between the target and each crystal to absorb beta rays. The procedure consisted of irradiating the target, interrupting the beam by means of the cam timer and pneumatically-operated beam stopper, and counting during the beam-off part of the cycle. The coincidence spectrum was displayed on a 100-channel pulse-height analyzer.

As a test of the method we examined the spectrum of gamma rays in coincidence with gamma rays of >4 Mev occuring in the decay of N^{16} using the target material described in the second section. The 2.75-Mev gamma ray, which is known[12] to follow a 1.1% beta-ray branch to a level in O^{16} at 8.87 Mev and to be in coincidence with gamma rays of 6.14 Mev, was observed clearly.

Similar measurements on C^{15} failed to reveal any gamma-ray lines between 0.7 and 4 Mev in coincidence with the 5.3-Mev gamma ray. An upper limit of 0.3% per decay may be placed on the intensity of such coincident gamma rays in the energy region of 2–3 Mev.

Actually, one might expect low-spin states in N^{15} to decay preferentially to the ground state rather than through one of the 5.3-Mev levels. Our next set of experiments, therefore, consisted of a search for high-energy gamma rays by means of a 3-crystal pair spectrometer. The arrangement was similar to that described earlier[13] except that the center crystal was $1\frac{1}{2}$ inches in diameter and 2 inches long and the side crystals were both 3×3 inches. An additional function of the cam timer in this case was to remove the voltage from the center photomultiplier tube during the deuteron bombardment of the target so as to avoid the effects of the high flux of prompt gamma radiation. The conical collimator between the target and center crystal was placed with its axis at an angle of $\sim30°$ to the beam so as to reduce the chance of detecting prompt gamma rays from the beam stopper and elsewhere in the Van de Graaff. In order to discriminate against the intense annihilation radiation associated with the production of 10-min N^{13} from the C^{12} in the target and also to absorb the C^{15} beta rays, a $\frac{1}{2}$-inch-thick lead plate was placed between the conical collimator and the center crystal.

The results of a check experiment on N^{16} activity are given in curve A of Fig. 8 which shows the 3-crystal pair spectrum obtained in a run of 2-hours actual counting time. Activation of the target with a 0.1-μamp beam at 2.5 Mev resulted in a singles counting rate of 14 000/sec in the center crystal and a 3-crystal rate of ~300 counts/min per channel at the 6.14-Mev peak. The 8.87-Mev line has been observed[14,15] previously only

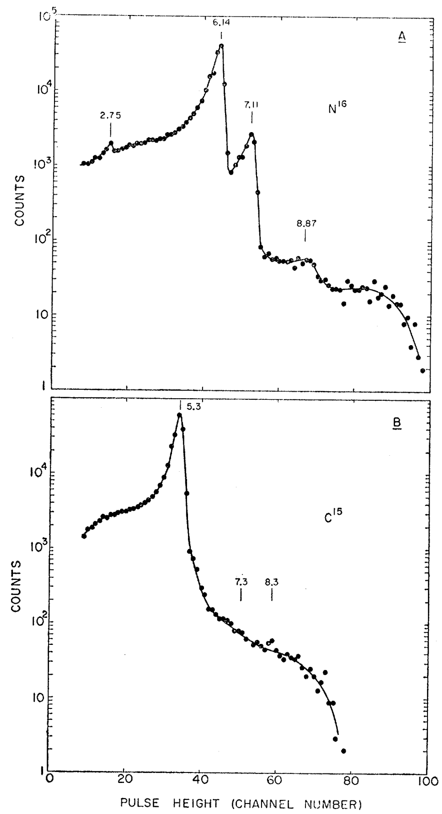

FIG. 8. Three-crystal pair spectra. Curve A–N^{16}; Curve B–C^{15}. Energies in Mev of known gamma rays or levels are indicated. Note: the constant of pulse height *versus* pair-line energy is slightly different for the two curves.

[12] Wilkinson, Toppel, and Alburger, Phys. Rev. **101**, 673 (1956).
[13] D. E. Alburger and B. J. Toppel, Phys. Rev. **100**, 1357 (1955).
[14] Bent, Kruse, Lidofsky, and Eklund, Bull. Am. Phys. Soc. **2**, 52 (1957).
[15] McCrary, Bonner, and Ranken, Phys. Rev. **108**, 392 (1957).

in the $F^{19}(p,\alpha)O^{16}$ reaction. In the beta decay of N^{16} it should occur to the extent of 0.1% per decay, or a factor of 700 lower than the 6.14-Mev line, on the basis of the known beta- and gamma-ray branching intensities. Figure 8(A) seems to indicate the presence of the 8.87-Mev gamma-ray line superposed on an underlying background which we attribute to pulse pile-up. The intensity of the line corresponds to a gamma ray 1/(800 ±200) as strong as the 6.14-Mev gamma ray. Both this result and the gamma-ray intensity ratio 6.14/7.11 =13±1.5 derived from Fig. 8(A) agree with the decay scheme of N^{16} proposed earlier.[2]

In Fig. 8(B) we show the 3-crystal pair spectrum of C^{15} obtained in $4\frac{1}{2}$ hours of actual counting time (10 hours total). With a 2-μa beam at 2.8 Mev, the singles and coincidence counting rates were only slightly lower than in the N^{16} run. Although several points at the 8.3-Mev position are above the smooth curve of background pile-up by slightly more than the probable errors, we can claim no positive evidence for any but the 5.3-Mev gamma ray. We place upper limits of 0.05% per decay on the intensities of the 7.3- and 8.3-Mev gamma-ray transitions whose predicted peak positions are indicated in the figure. There is furthermore no evidence for lower energy gamma-ray peaks. From a comparison between curves *A* and *B*, and knowing that the 2.75-Mev peak in curve *A* corresponds to a gamma-ray intensity of 1% per decay, we can place an upper limit of 0.5% per decay on C^{15} gamma rays between 2 and 3 Mev.

We have also searched for beta decay of O^{19} to the 2.78-Mev (7/2, 9/2) state of F^{19} by measuring the gamma-ray singles and 3-crystal pair spectra. This state is known[1] to decay to the 0.198-Mev level with the emission of 2.6-Mev gamma radiation. An upper limit of 0.15% per decay is placed on the beta decay of O^{19} to the 2.78-Mev state and this corresponds to a lower limit of 6.3 for the log *ft* value.

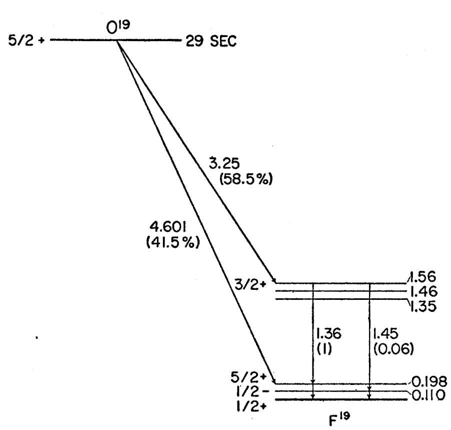

FIG. 9. Decay scheme of O^{19}.

DISCUSSION

N^{16}

The characteristics of N^{16} are well established from earlier work.[1,2] Our examination of this activity had as its primary objective the testing of the spectrometer on a beta-ray transition of known shape and of about the same energy as is involved in the decay of C^{15}. As we have seen the correct unique first-forbidden shape was found and a good value for the end point was obtained. This gives us confidence in the correct functioning of the spectrometer in a new region of beta-ray energy. A secondary objective was the removal of a discrepancy as to the intensity of the low-energy branch to the 7.11-Mev state of O^{16} between gamma-ray measurements and earlier beta-ray spectrometer measurements. This was also successful.

We summarize in Table II what we believe to be the best available data[2,12,16,17] on the beta decay of N^{16}. In drawing up this table we have used a mean value[1] of 7.37±0.04 seconds for the half-life of N^{16}. These data are not sufficiently different from those current at the

TABLE II. Beta-ray branches in the decay of N^{16}.[a]

$E_{\beta\max}$ (Mev)	State of O^{16} (Mev) and spin-parity	Percent branch	log f_0t (exp)	log f_0t (theor)
10.40	ground, 0+	26±2	6.69±0.04	6.5
···	6.05, 0+	⩽0.015	⩾8.2	···
4.26	6.14, 3−	68±2	4.52±0.02	4.65
3.29	7.11, 1−	4.9±0.4	5.10±0.04	7.9
1.53	8.87, 2−	1.0±0.2	4.3 ±0.1	4.2

[a] References 2, 12, 16, 17, and present work.

time that Elliott and Flowers[17] published their successful calculations to warrant a recomparison of theory and experiment.

O^{19}

The decay scheme of O^{19} (see Fig. 9) is well known[10] and the present measurements are in complete accord with the earlier work. Their special contribution is to provide a more accurate measurement of the branching ratio between the 1.56-Mev and 0.198-Mev states and to give good values for the beta-ray energies. These results have already been reported above.

The question of the absence of the transitions to the $\frac{1}{2}+$ ground state of F^{19} is an important one since it is an approach to the ground state spin of O^{19}. According to the shell model[18] the ground state of O^{19} is $\frac{5}{2}+$ while according to the rotational model[19] it is $\frac{3}{2}+$. Experimentally we have $\frac{3}{2}+$ or $\frac{5}{2}+$ with the latter preferred[10] simply because the ground-state transition has log

[16] B. J. Toppel, Phys. Rev. **103**, 141 (1956).
[17] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957).
[18] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955).
[19] E. B. Paul, Phil. Mag. **2**, 311 (1957). G. Rakavy, Nuclear Phys. **4**, 375 (1957).

$ft>6.5$. However on the collective picture the $O^{19}(\frac{3}{2}+)$ to $F^{19}(\frac{1}{2}+)$ transition would be of $K=\frac{3}{2}$ to $K=\frac{1}{2}$ and would be asymptotically hindered. It is therefore important to confirm or sharpen the limit on the ground-state transition. The present approach of direct beta-spectrum measurement could not be expected to reveal directly a weak branch to the ground state. It might, however, do so indirectly by showing an apparent end point inconsistent with a simple transition to the 0.198-Mev state. We have made Kurie plots of constructed beta-ray spectra composed of various relative intensities I_β of two allowed components having end points of 4.60 and 4.80 Mev. In all cases the Kurie plot in the region above 3.3 Mev is linear and its extrapolated end point lies above 4.60 Mev by an amount closely equal to $[I_{4.8}/(I_{4.6}+I_{4.8})]\times 0.20$ Mev. We may therefore estimate the relative strength of the ground-state component by comparing our measured extrapolated end point of 4.601 ± 0.015 Mev with that expected from other data for a transition to the 0.198-Mev state. There are two cycles of accurately-measured Q values that can be used to determine the mass difference Δ

TABLE III. Beta-ray branches in the decay of O^{19}.

$E_{\beta\max}$ (Mev)	State of F^{19} (Mev) and spin-parity	Percent branch	log ft (exp)	log f_0t (theor)[a]
...	ground, 1/2+	$\leqslant 4$	$\geqslant 6.5$	...
4.601	0.198, 5/2+	41.5_{-5}^{+2}	$5.45_{-0.03}^{+0.06}$	~ 6.4
3.25	1.56, 3/2+	58.5 ± 2	4.51 ± 0.03	4.6
...	2.78, 7/2, 9/2	$\leqslant 0.15$	$\geqslant 6.3$	...

[a] See reference 18.

between O^{19} and F^{19}. They are:

$$O^{16}(d,p)O^{17}(d,p)O^{18}(d,p)O^{19}(\Delta)F^{19}(p,\alpha)O^{16},$$

and

$$O^{18}(d,p)O^{19}(\Delta)F^{19}(d,t \text{ and } He^3,\alpha)F^{18}(n,p)O^{18}.$$

In the second cycle two independent measurements link F^{19} and F^{18} and the last reaction is written backwards. The data of the literature[1] yield $\Delta=4.815\pm 0.016$ Mev and 4.793 ± 0.014 Mev for these two cycles, respectively. Since the only reaction in common between the cycles is $O^{18}(d,p)O^{19}$ which contributes little (3 kev) to the error of either cycle we may combine them to find $O^{19}-F^{19}=4.803\pm 0.012$ Mev (allowing for common contributions to error through the simple particles). If the high-energy transition of O^{19} is purely to the 0.198-Mev state of F^{19}, we therefore expect an end point of 4.604 ± 0.012 Mev (allowing 0.001 Mev for recoil) to compare with our measured value of 4.601 ± 0.015 Mev. These two figures agree well within the combined error of 0.019 Mev. By comparing the error with the difference of 0.198 Mev in the end-point energies, it appears unlikely that there can be more than 10% by relative intensity of the ground-state transition involved in the decay as compared with the transition to the second excited state. This corresponds to log $ft\geqslant 6.5$ for the ground-state transition, the same limit as reached in other work[10] which used a quite different method.

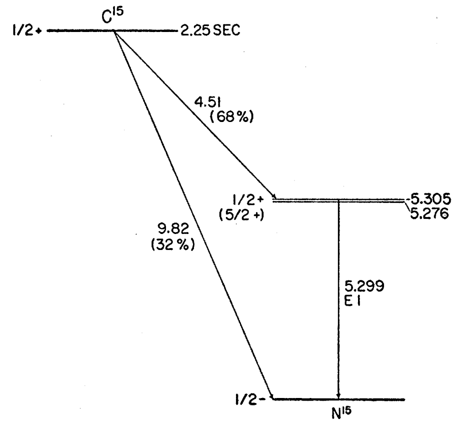

FIG. 10. Decay scheme of C^{15}.

We summarize in Table III and in Fig. 9 the present data for the beta-ray transitions of O^{19} (rather sharp limits are available for transitions to other low-lying levels but these are discussed in detail elsewhere[10]). In drawing up Table III, we have used a half-life of 29.4 ± 1 seconds.[1] The intensity of the 4.601-Mev branch is assigned a larger limit of error on the lower side because of the possible presence of a ground-state beta-ray transition.

Just as for N^{16}, the changes in the log ft values consequent upon the present work are not great enough to warrant a fresh comparison with theory.[18] The limit on the decay to the 2.78-Mev state of F^{19} suggests that the transition is at least first-forbidden. If we may anticipate that this state is of even parity and if the ground state[10] of O^{19} is indeed $\frac{5}{2}+$, then our result favors the $J=9/2$ alternative which agrees with the theoretical prediction.[18]

C^{15}

The chief objective of this work was a study of the C^{15} decay. (For the discussion which follows, refer to Fig. 10 and to the level diagram for N^{15} given in reference 1.) C^{15} is interesting because it contains 9 neutrons so the last is presumably in the mixed $2s$-$1d$ shell. We should therefore expect C^{15} to be $\frac{5}{2}+(1d_{\frac{5}{2}})$ or $\frac{1}{2}+(2s_{\frac{1}{2}})$. The expected $\frac{3}{2}+$ $(1d_{\frac{3}{2}})$ state should be somewhat higher up. To speak of C^{15} in this way as a one-particle nucleus is, of course, incorrect but is encouraged by the large excitation (at least 6.6 Mev) of the first even-parity excited state of the parent C^{14}. This simple view is justified by the results of the full intermediate-coupling calculation[20] which treats it as the 3-body $p^{-2}(2s, 1d)$ and which shows the lowest two states of C^{15} to be $\frac{5}{2}+$ and $\frac{1}{2}+$ and to be rather good one-particle

[20] E. C. Halbert and J. B. French, Phys. Rev. **105**, 1563 (1957). See also reference 17.

states. Which of the two should be the ground state is not clear from the calculation; they are predicted as being very close together. In fact,[1] the lowest experimental excited states of C^{15} are at 0.66 and 2.48 Mev, a pattern qualitatively consistent with the simple expectation. If now the ground state were $\frac{5}{2}+$, the transition to the N^{15} ground state $(\frac{1}{2}-)$ would have the unique first forbidden shape. We have already noted (Fig. 4 compare Fig. 2) that this is certainly not the case and so the $\frac{5}{2}+$ possibility is eliminated. We have also noted, however, that the spectrum has very accurately the allowed shape, at least in the region accessible to us before the lower energy branch is encountered. At first sight this does not seem surprising because it is a general rule[21] that first forbidden transitions of $\Delta J=0$ or 1 have the allowed shape. The reason for this is clear on examining the form of the correction factor to the allowed shape for such transitions which may be written

$$C\sim O(E_B)+O(p,q),$$

where E_B is the electrostatic energy at the edge of the nucleus and p,q are the lepton momenta. We usually encounter first forbidden transitions in nuclei of medium or heavy weight where $E_B\sim 10$ Mev or more and where the beta transition is of 1 or 2 Mev. Under these circumstances, the electrostatic term dominates the momentum term and so the correction factor is almost a constant. With C^{15}, however, the situation is reversed: $E_B\sim 2$ Mev and the transition energy ~ 10 Mev. We should therefore have expected a strong departure from the allowed shape if $J=\frac{1}{2}+$ or $\frac{3}{2}+$ and should only have expected an accurately allowed shape if the transition were fact allowed, *viz.*, odd parity for C^{15}.

This last possibility is most unpalatable and the second part of this investigation was directed towards the problem of the parity of C^{15}. This we are able to attack because a transition to the (5.28–5.31)-Mev doublet of N^{15} is certainly allowed (log $ft=4.1$). Even if the decay takes place to both members of the doublet this remark holds true. Our task is accordingly to determine to which member of the doublet the decay leads and then to fix the parity of that member which gives us the parity of C^{15}.

The lower doublet member is formed by stripping[1] in the reaction $N^{14}(d,p)N^{15}$ with $l=2$ which fixes its parity as even and its spin as $J=\frac{1}{2}$ to $\frac{7}{2}$. We may regard the possibilities $J=\frac{1}{2}$ and $\frac{3}{2}$ as relatively unlikely, however, because they could be formed by $l=0$ which is not seen. The shell model in intermediate coupling[20] is firm that the lowest even parity $T=\frac{1}{2}$ state of N^{15} should have $J=\frac{5}{2}$ and it seems likely that this is correct. The experimental reduced width of this state is in good accord with the prediction of the model. In this case, we should not expect C^{15} to decay to this state with log $ft=4.1$ if the parity of C^{15} were odd (a first forbidden transition), nor if C^{15} were $\frac{1}{2}+$ because the transition would in the latter case be second-forbidden. As we have seen this state is indeed not favored in the decay which goes largely or wholly to the upper doublet member.

The upper doublet member therefore fixes the parity of C^{15}. Unfortunately its own parity is unknown. It is formed in the $N^{14}(d,p)N^{15}$ reaction with a low, more-or-less isotropic cross section[1] which does not admit of a stripping interpretation. A weak argument against odd parity is that the $\frac{3}{2}-$ ($1p_{\frac{3}{2}}$ hole) state of N^{15}, which together with the $\frac{1}{2}-$ ground state completes the remnants of the $1p$-shell, appears to be that at 6.33 Mev and so we should not expect any more odd-parity states until considerably higher because these will be states of double excitation. We unhappily find a rapid gegenbeispiel in the neighboring nucleus O^{16} which has even-parity excited states equally numerous with odd-parity ones, but in fact in N^{15} no other odd-parity state is known below 10 Mev which encourages our argument. As we have seen, our measurements of the internal pair formation coefficient strongly suggest that the transition to ground from this state is $E1$ which confirms that it is of even parity, $J=\frac{1}{2}+$ or $\frac{3}{2}+$, and this in turn implies that C^{15} is $J=\frac{1}{2}+$ or $\frac{3}{2}+$. The theoretical indication is clearly in favor of $\frac{1}{2}+$ for C^{15}. Other evidence comes from N^{15}. A state of $\frac{1}{2}+$ at 11.61 Mev is found to have a large reduced width for proton emission and a very small ($\sim 10^{-3}$ single-particle units) width for neutron emission,[22] a fact that suggests strongly that it has $T=\frac{3}{2}$ and so must be found in C^{15}. We accept this for the following discussion. It has already been suggested[22] that this state of N^{15} may correspond to the ground state of C^{15}. To predict the excitation in C^{15} corresponding to 11.61 Mev in N^{15}, we resort to an automatic procedure already described.[23] The ground state of C^{14} is 0.16 Mev above the ground state of N^{14} but corresponds to the $0+$ $T=1$ state at 2.31 Mev, i.e., the Coulomb plus n-p mass difference shift from N^{14} to C^{14} is 2.15 Mev. If we make the approximate $A^{\frac{1}{3}}$ correction,[23] we should expect a corresponding shift of 2.10 Mev in the $A=15$ system. We therefore expect the state in C^{15} analogous to that at 11.61 Mev in N^{15} to be 9.51 Mev above the ground state of N^{15}. The same prediction based on the energy difference of the $N^{13}-C^{13}$ mirror pair gives 9.49 Mev in good agreement. In fact the energy is 9.8 Mev. This discrepancy of 0.30 Mev between the ground state of the $T_z=X$ nucleus and the excitation of the analog state in the $T_z=X-1$ nucleus is in the same sense and of the same order as those found in comparable cases where $X=1$ and the self-conjugate nucleus is even-even.[23] It is doubtless due to the great density of states in the $T_z=X-1$ nucleus under these circumstances which results in a depression there of the analog state.

[21] See, e.g., M. G. Mayer, reference 5, Chap. XVI, p. 433.

[22] Bartholomew, Litherland, Paul, and Gove, Can. J. Phys. **34**, 147 (1956).

[23] D. H. Wilkinson, Phil. Mag. **1**, 1031 (1956).

Furthermore if the 11.61-Mev $\frac{1}{2}+$, $T=\frac{3}{2}$, state of N^{15} does not correspond to the ground state of C^{15}, the resulting discrepancy would be unacceptable—at least 1.0 Mev—since the first excited state of C^{15} is at 0.66 Mev. These arguments strongly favor $\frac{1}{2}+$ for C^{15}. Stripping measurements[1,24] on $C^{14}(d,p)C^{15}$ are consistent with this assignment though do not of themselves establish it.

Comparison with the theoretical intermediate coupling scheme also favors the $\frac{1}{2}+$ alternative for the 5.305-Mev state of N^{15}. Of the lowest seven states belonging to $p^{-2}(2s, 1d)$, six are well identified with experimental states, the lower theoretical $\frac{1}{2}+$ state remaining for identification with the 5.305-Mev $\frac{1}{2}+$ or $\frac{3}{2}+$ state. This identification is encouraged by the comparison of the feebleness of the stripping to this state with the low values of the theoretical reduced widths (0.016 for $l=0$, and 0.006 for $l=2$ in the appropriate single-particle units). We may also consider the possibility of its identification with the lowest $\frac{3}{2}+$ state of the model. This we reject: firstly, because that state has a large theoretical reduced width for $l=0$ and, secondly, because there is already a satisfactory identification with the experimental $\frac{1}{2}+$, $\frac{3}{2}+$ state at 7.31 Mev which shows experimentally a large $l=0$ reduced width.

It therefore seems likely that the 5.305-Mev state is the missing $\frac{1}{2}+$ state of the intermediate-coupling model. Other possibilities are that it is a more complicated state than $p^{-2}(2s,1d)$ or that it is perhaps $1s^3p^{12}$. Either alternative would explain the low isotropic $N^{14}(d,p)N^{15}$ cross section. They are however eliminated by the very fast beta transition to this state from C^{15}. This would not be expected if the N^{15} state were complicated and would be forbidden if it were $1s^3p^{12}$.

We may conclude our comparison with the intermediate-coupling model by considering two more predictions of that model, *viz*, the energy of the C^{15} ground state and the speed of the beta-ray transitions to states of N^{15}. The theoretical excitation of the lowest $\frac{1}{2}+$, $T=\frac{3}{2}$ state of N^{15} is about 12.3 Mev. If we subtract the semiempirical Coulomb plus n-p mass difference correction of 2.1 Mev discussed above, we predict $C^{15}-N^{15}=10.2$ Mev which is in quite good agreement with the experimental 9.8 Mev. The theoretical log ft value for the beta transition in question is about 4.8 which is in moderate but not good agreement with the experimental figure of 4.1. At least the transition is predicted to be fast. The theoretical predictions about the speeds of allowed transitions to higher states of N^{15} are not obviously in conflict with the limits established in this work.

We finally return to the ground-state beta-ray transition of C^{15} and to the puzzle of why it has so accurately the allowed shape. Since the intermediate-coupling

[24] W. E. Moore and J. N. McGruer, Bull. Am. Phys. Soc. Ser. II, 4, 17 (1959).

TABLE IV. Beta-ray branches in the decay of C^{15}.

$E_{\beta max}$ (Mev)	State of N^{15} (Mev) and spin-parity	Percent branch	log f_0t (exp)	log f_0t (theor)
9.8	ground, 1/2−	32±2	5.97±0.04	5.8[c]
4.5	5.305, 1/2+	68±2	4.07±0.03	4.80[d]
···	7.31, 1/2+, 3/2+	⩽0.05[a]	⩾6.0[a]	6.49[e]
		⩽0.3[b]	⩾5.2[b]	
···	8.32, 1/2+, 3/2+	⩽0.05[a]	⩾5.0[a]	4.51[e]
		⩽0.3[b]	⩾4.2[b]	

[a] Assuming de-excitation predominantly by a ground-state gamma-ray transition.
[b] Assuming de-excitation predominantly by a cascade gamma-ray transition.
[c] Single-particle calculation by J. S. Thomson—see text.
[d] See reference 20.
[e] Calculation by J. B. French and S. Iwao using the full intermediate-coupling wave functions of reference 20.

model suggests that the C^{15} ground state is almost wholly $p^{-2}2s$ the spectrum and the log ft value are easily calculated. This has been done by J. S. Thomson of the Clarendon Laboratory using A and V couplings and harmonic oscillator wave functions adjusted to give the correct size for the nucleus as indicated by the systematics of fast electron scattering. The calculations were made with an rms radius of 2.52×10^{-13} cm and with $C_A=-1.2C_V$. Good agreement with the experimental log ft value of 6.0 is found and the shape correction factor for that portion of the beta-ray spectrum which is accessible to us (see Figs. 3 and 4) is remarkably independent of beta-ray momentum. Considerable divergence from the allowed shape is found in the region that is obscured by the low-energy branch and it is clear from the strong momentum dependence of the many individual matrix elements that the constancy of the shape factor above 5 Mev is due chiefly to chance. It appears then that the allowed shape of Fig. 4 is to some degree explained. A divergence between the theoretical and experimental shapes is, however, apparent and the significance of this must await the calculation using the full wave functions.[25] We remark in passing that the C^{15} decay, if indeed it is $\frac{1}{2}+$ to $\frac{1}{2}-$, may have some pseudoscalar contribution. This will affect the spectral shape and might be detected by measurement of the longitudinal polarization of the beta particles.

We summarize in Table IV and in Fig. 10 the data on the decay of C^{15}. We have used a half-life of 2.25 ±0.05 seconds[1] for C^{15}.

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[25] In none of the experimental results given in this paper have we applied any radiative correction.