THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 179, NO. 4 — 20 MARCH 1969

Beta Decays of C^{15}, F^{17}, and F^{20}†

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(Received 27 September 1968)

β-ray branches in the decays of C^{15}, F^{17}, and F^{20} have been investigated by measuring the γ-ray spectra from these activities with a 22-cc Ge(Li) detector. The activities were formed by deuteron bombardment of various targets with a chopped Van de Graaff beam. Previously observed C^{15} β-ray branches to the 8312- and 9052-keV states of N^{15} were confirmed, the branches being $[(5.0\pm0.6)\times10^{-4}; \log ft=5.06\pm0.06]$ and $[(3.5\pm0.5)\times10^{-4}; \log ft=3.99\pm0.07]$, respectively, and one new branch was found leading to the 7300-keV state $[(0.8\pm0.2)\times10^{-4}; \log ft=6.82\pm0.13]$. There is also weak evidence for a β-ray branch to the 8570-keV state of $N^{15}[\leq2.8\times10^{-4}; \log ft\geq5.0]$. The limit on the β branching of F^{17} to the 871-keV state of O^{17} is $<3.4\times10^{-4}$, corresponding to $\log ft>5.6$. In F^{20} decay, lifetime measurements have confirmed that a weak 3.3-MeV γ ray is associated with this activity resulting from a β-ray branch to the 4.97-MeV state of $Ne^{20}[(1.7\pm0.3)\times10^{-4}; \log ft=6.89\pm0.08]$. From simultaneous measurements on the γ rays occurring in F^{20} and B^{12} decays, the energy of the F^{20} γ ray is 3334.3 ± 0.7 keV, and thus the Ne^{20} level has an energy of 4968.3 ± 0.8 keV.

INTRODUCTION

PREVIOUS studies[1] of short-lived activities were made at Brookhaven several years ago by the use of a 3.6-cc Ge(Li) γ-ray detector and a chopped Van de Graaff beam for producing the activites. One of the purposes of that work was to search for weak β-ray branching by observing the subsequent γ-ray emission. C^{15} was studied extensively since it was expected that in addition to the known β-ray branches to the ground and 5299-keV states of N^{15}, allowed β-ray branches should take place to the states at 7300, 8312, 8570, and 9052 keV, all of which have spin parities[2] of $J^\pi=\frac{1}{2}^+$ or $\frac{3}{2}^+$ (C^{15} has $J^\pi=\frac{1}{2}^+$). The branches to only the 8312- and 9052-keV levels were found, and the errors in their branching intensities were large.

In F^{20} decay, a weak peak was observed[1] in the high-energy region of the γ-ray spectrum, and it was assigned as the 2-escape peak of a γ ray of 3334 ± 8 keV. The data were interpreted as corresponding to a β-ray branch of 1.7×10^{-4} to the 4.97-MeV state of Ne^{20} ($\log ft=6.9\pm0.2$), a state that is known to decay by a $4.97\to1.63\to0$ γ-γ cascade. During the course of the present work, it was learned that this same γ-ray transition had been observed by Kavanagh[3] in γ-γ coincidence measurements on F^{20} using NaI(Tl) detectors. Although no final value was derived for the β-ray branching ratio to the 4.97-MeV state, Kavanagh found that the results of several measurements were consistent with the value obtained at Brookhaven.[1]

Significant advances in the technology of Ge(Li) detectors have been made in the past few years resulting in the availability of detectors with larger volume and improved energy resolution. In the present work we have utilized a 22-cc detector, having a resolution of 3.0 keV for the γ rays of Co^{60}, to re-investigate the decays of C^{15}, F^{17}, and F^{20}. C^{15} was studied in order to search for the two remaining allowed β-ray branches to the 7300- and 8570-keV states of N^{15}, as well as to improve on the accuracy of the branching ratios to the 8312- and 9052-keV states. F^{20} was investigated to confirm that the 3.3-MeV γ ray exists and belongs to F^{20} decay, and to establish the energy of this transition with greater accuracy. A brief experiment on the decay

† Research at Brookhaven National Laboratory carried out under the auspices of the U.S. Atomic Energy Commission.
[1] D. E. Alburger and K. W. Jones, Phys. Rev. **149**, 743 (1966).
[2] E. K. Warburton, J. W. Olness, and D. E. Alburger, Phys. Rev. **140**, B1202 (1965).
[3] R. W. Kavanagh (private communication).

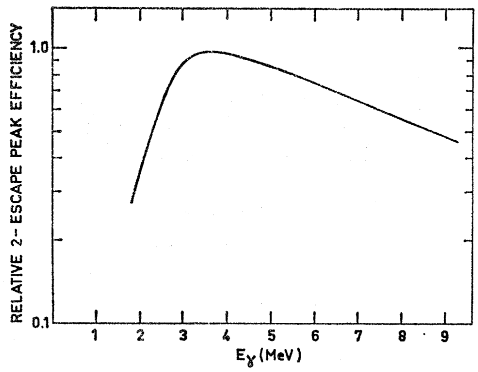


FIG. 1. Relative 2-escape peak efficiency versus γ-ray energy for the 22-cc Ge(Li) detector used in this work.

of F^{17} was carried out in order to further sharpen the limit[1] on the possible branch to the 871-keV state of O^{17}.

EXPERIMENTAL METHODS

The activities were formed by bombarding various targets with a beam of deuterons from the 5.5-MV Van de Graaff accelerator at the Centre de Recherches Nucléaires, Strasbourg, France. For the work on C^{15} and F^{17}, and part of the work on F^{20}, a fast mechanical beam chopper[4] together with a timing and gating system, was used to form and count the delayed radiations. The Ge(Li) detector was placed close to the target at 90° to the beam and lead bricks were arranged so as to absorb γ-rays coming directly from the chopper, the latter being situated ~20 ft up stream from the target. The γ-ray spectra were recorded in a 4096-channel pulse-height analyzer. Gain stabilization of the detecting system was employed for the C^{15} studies.

A second device[5] was used for the remaining measurements on the decay of F^{20}. This consisted of a magnetic beam deflector and a timing system which switched the beam onto the target for a 10-sec bombardment and then off again for 20 sec of counting. After each bombardment, a delayed spectrum was stored in one 2048-channel section of the analyzer for 10 sec. A second spectrum was stored in the other 2048-channel section of the analyzer during the immediately following 10-sec interval, thereby allowing the decay rates of various spectral lines to be determined. This cycle was repeated continuously to accumulate counts in the two spectra.

Simultaneous measurements on the γ rays from F^{20} and B^{12} were made by using a split-target technique.[6] By means of an external positioning screw the ratio of intensities of the lines from the two activities could be varied by changing the relative amounts of the two targets exposed to the beam.

For the detection of γ rays by a 22-cc Ge(Li) detector the 2-excape peak predominates in the γ-ray energy region, 3–9 MeV, studied in the present work. It was therefore important to know the 2-escape peak efficiency as a function of γ-ray energy in order to derive relative γ-ray intensities. Figure 1 shows the 2-escape efficiency curve developed for this particular detector based on various spectra recorded in experiments at Strasbourg.

EXPERIMENTAL RESULTS AND DISCUSSION

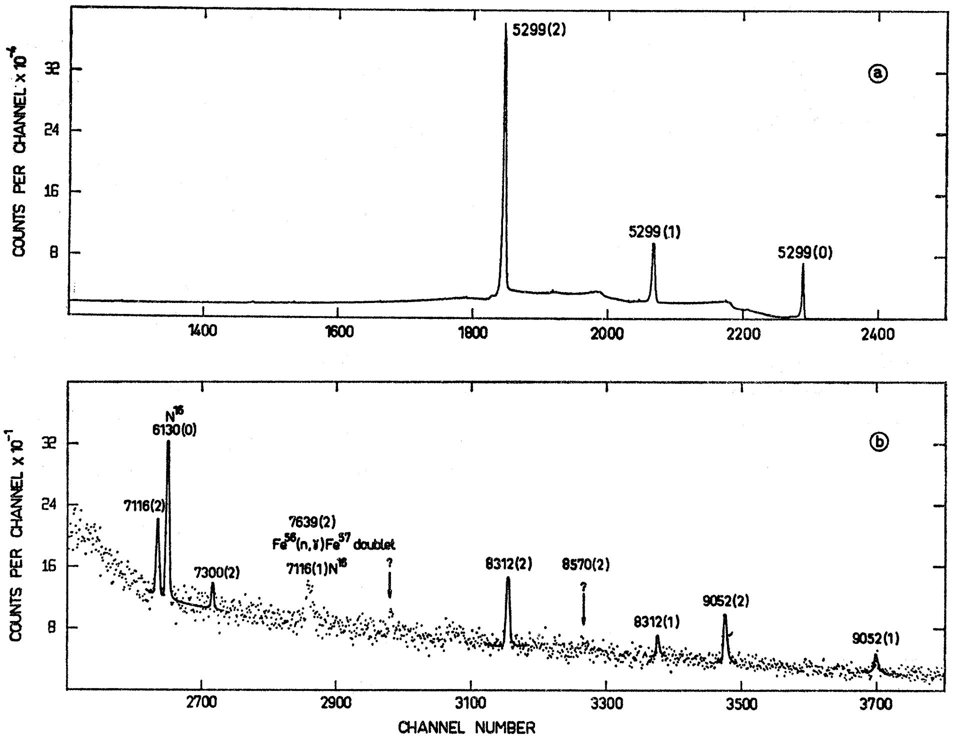
C^{15}

The C^{14} target (0.7 mg/cm^2 thick and enriched to 80% C^{14}) was the same as that used in the earlier experiments.[1] It was bombarded with a chopped beam of 2.7-MeV deuterons at an average beam current of 0.06 μA. Absorbers of 11.5 mm of Al and 10 mm of Pb were placed between the target and the detector in order to stop the energetic C^{15} β rays and to discriminate against the strong 0.511-MeV γ rays from N^{13} activity.

Figure 2 shows the spectrum obtained in a total bombardment of 9660 μC, or about 45 h of beam time. Assignments have been made to all of the peaks in this spectrum with the exception of a possible weak line at channel 2983. If it is real this line would correspond to the 2-escape peak of a γ ray having an energy of 7914 keV, but we offer no explanation for its origin. Comparison of Fig. 2 with the older work[1] shows that in the present case not only do the 2-escape peaks of the 8312- and 9052-keV γ rays stand out very much more clearly but the corresponding 1-escape peaks of these γ rays appear as well. At channel 2719 is a weak line that is assigned as the 2-escape peak of 7300-keV γ rays following the β-ray branching to this state in N^{15}. A possible peak at channel 3269 in Fig. 2 would correspond to the 2-escape peak of a γ ray of 8570 keV but because of the uncertainties, as discussed below, the peak has not been drawn in. The calculated position is indicated in Fig. 2 by an arrow.

Lines in Fig. 2 that are not associated with C^{15} decay include the two N^{16} peaks in the vicinity of channel 2640 [resulting from the $N^{15}(d,p)N^{16}$ reaction on N^{15} contamination in the target] and the broad peak near channel 2860. In view of the observed intensity ratios of the 2-escape to 1-escape peaks in Fig. 2 for the 5299-, 8312-, and 9052-keV γ rays, the 1-escape peak of the N^{16} 7116-keV γ ray must be present at channel 2858 and it must have an amplitude equal to about $\frac{1}{3}$ the maximum amplitude of the broad peak. The major part of the yield in this region, however, is assigned to the reaction $Fe^{56}(n,\gamma)Fe^{57}$ (as in the earlier work[1]) resulting from neutrons produced at the chopper and captured in iron near the detector. In the present case the resolution of the detector is good enough so that the relatively greater width of

[4] G. Frick, A. Gallmann, D. E. Alburger, D. H. Wilkinson, and J. P. Coffin, Phys. Rev. **132**, 2169 (1963).
[5] R. W. Kavanagh, A. Gallmann, E. Aslanides, F. Jundt, and E. Jacobs, Phys. Rev. **175**, 1426 (1968).
[6] C. Chasman, K. W. Jones, R. A. Ristinen, and D. E. Alburger, Phys. Rev. **159**, 830 (1967).



2. γ-ray spectrum of C^{15} plus contaminant background observed with a 22-cc Ge(Li) detector. Numbers in parentheses indicate whether a peak is full-energy (0), 1-escape (1), or 2-escape (2).

this peak is quite apparent, and in fact, the peak can be fitted with a doublet having a separation of 14 keV. The structure is consistent with the Fe(n, γ) γ-ray spectrum first obtained by Ewan and Tavendale.[7] More recently the energies of the Fe(n, γ) lines have been measured by Spilling *et al.*,[8] who report values of 7631.6±0.5 and 7645.8±0.5 keV for the two γ rays. According to our energy calibration the 2-escape peaks of these two γ rays should then occur in Fig. 2 at channels 2860.4 and 2866.6, in good agreement with the positions of the doublet components determined by a hand analysis of the spectrum.

Two regions of particular interest in the C^{15} γ-ray spectrum of Fig. 2 are given in more detail in Fig. 3. Curve a is the data for the 7300-keV 2-escape peak and shows the computer fit according to which the net peak area is 136±40 counts. Similarly, curve b of Fig. 3 shows the region of the expected 8570-keV 2-escape peak. The computer program finds a peak at channel 3268 (in agreement with the expected location) having an area of 80±22 counts. However, from a study of χ^2 for the fit to the data for various forced values of the area, there is considerable doubt as to the certainty of the 8570 2-escape peak. Although a γ-ray line may be present, we assign an upper limit of 100 counts to its area.

A summary of the results on C^{15} decay is given in Table I. Relative β-ray branching ratios were determined from the areas under the various 2-escape peaks, after correcting for γ-ray absorption, for the 2-escape peak efficiency according to Fig. 1, and also for the value of the ground-state γ-ray branching ratio known for each state.[1,2] The β-ray branching intensities were then determined with respect to the known 68% branch to the 5299-keV level. Finally, the logft values were calculated by using a computer code.

Logft values for the C^{15} β-ray branches to the 8312- and 9052-keV levels in Table I are somewhat higher than in the earlier work,[1] although within their larger errors the previous results are in agreement with those now reported. It may be noted that the new result on the logft value for the branch to the 7300-keV state is somewhat greater than the theoretical calculation. The upper limit on the branch to the 8570-keV state has been reduced by a factor of 10 compared with the previous work,[1] but the present lower limit on the logft value is still consistent with an allowed β-ray transition. It is suspected that the 2-escape peak of the 8570-keV γ ray is really present, and that a run with even better resolution and/or satistics would establish it with certainty. We find no evidence for the β-ray branching of C^{15} to any of the other known

[7] G. T. Ewan and A. J. Tavendale, Nucl. Instr. Methods **26**, 183 (1964); see also *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Inc., New York, 1965), Vol. I, p. 803.

[8] P. Spilling, H. Gruppelaar, H. F. DeVries, and A. M. J. Spits, Nucl. Phys. **A113**, 395 (1968).

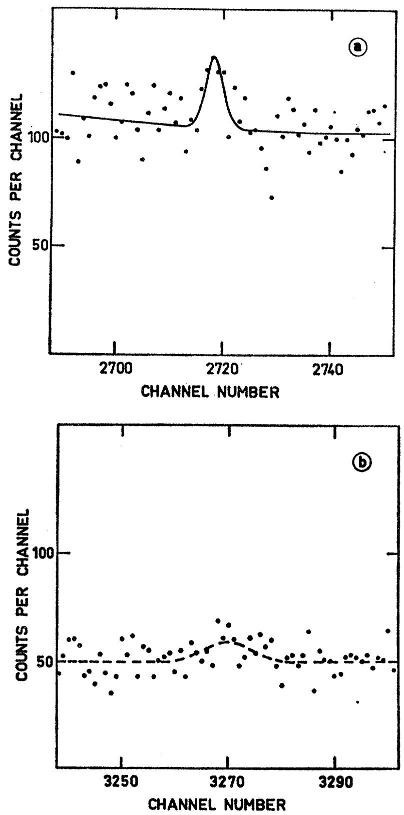


FIG. 3. Curve a—detail of the C^{15} spectrum of Fig. 2 in the vicinity of the 7300-keV 2-escape peak showing the computer fit to the data (solid line). Curve b—detail of the C^{15} spectrum in the vicinity of the expected 8570-keV 2-escape peak. The computer finds a peak but it is indicated with a dashed line since it represents an upper limit as explained in the text.

states[2] of N^{15}. However, none of these β-ray transitions would be allowed according to the present knowledge[2] of the spins and parities of the various states in N^{15} that could be reached energetically in C^{15} decay.

F^{17}

F^{17} decay was studied with the 22-cc Ge(Li) detector by following the same procedures as in earlier experiments.[1] Four runs were made in a search of possible 871-keV γ rays that would result from positron decay to this state of O^{17}. The upper limit for such a peak corresponds to a positron branch of $<3.4\times10^{-4}$. This is only a factor of 2 improvement on the previous upper limit[1] of 6×10^{-4}, and thus the limit of $\log ft >5.6$ for this branch is still consistent with the forbidden nature of the $\frac{5}{2}^+\to\frac{1}{2}^+$ positron transition $F^{17}\to O^{17}$ (871 keV).

TABLE I. β-ray branching intensities and $\log ft$ values for the decay of C^{15} to various states in N^{15}.

Level in N^{15} (keV)	Fractional β-ray branch	$\log ft$ (expt)	$\log ft$ (theoret)[a]
0	0.32 ± 0.02	5.96 ± 0.03	5.8
5299	0.68 ± 0.02	4.04 ± 0.02	4.80
7300	$(0.8\pm0.2)\times10^{-4}$	6.82 ± 0.13	6.49
8312	$(5.0\pm0.6)\times10^{-4}$	5.06 ± 0.06	4.51
8570	$\leq2.8\times10^{-4}$	≥5.0	
9052	$(3.5\pm0.5)\times10^{-4}$	3.99 ± 0.07	

[a] See D. E. Alburger, A. Gallmann, and D. H. Wilkinson, Phys. Rev. **116**, 939 (1959), where the theoretical calculations are summarized in Table IV, p. 949.

F^{20}

The F^{20} activity was formed by bombarding a 4-mg/cm^2-thick evaporated BaF_2 target with 2.0-MeV deuterons. The first set of experiments was carried out using the magnetic beam deflecting device[5] in order to detect the previously observed[1] γ ray of 3334 ± 8 keV and to assign it to the decay of F^{20}. The earlier

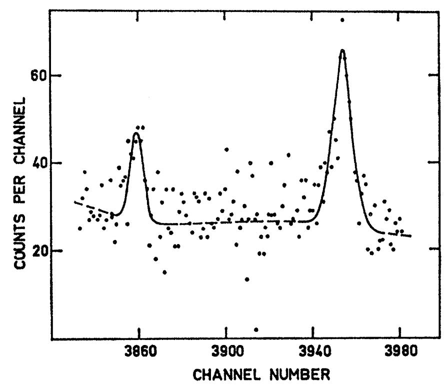


FIG. 4. Spectrum of $F^{20}+B^{12}$ γ rays observed with the 22-cc Ge(Li) detector in order to measure the energy of the F^{20} γ ray. The left-hand line is the full-energy-loss peak of the F^{20} 3.3-MeV γ ray while the right-hand line is the 2-escape peak of the B^{12} (4438.91 ± 0.31)-keV γ ray. The dispersion is 0.861 keV per channel.

presumption[1] that this γ ray results from the $4.97\to1.63$ transition in Ne^{20}, following a weak β-ray branch to the 4.97-MeV state, has been confirmed by Kavanagh[3] in the coincidence measurements mentioned previously.

All of the present observations were made on the full-energy-loss peak of the 3.3-MeV γ rays. The ratio of the intensity of this peak to that of the 1.63-MeV full-energy-loss peak was measured in the two time-delayed spectra separated by 10 sec, as described earlier; the total data accumulation time was several hours. After making the appropriate corrections for γ-ray efficiency versus energy, the branch to the 4.97-MeV state was determined to be $(1.6\pm0.4)\times10^{-4}$ from the first 10-sec spectrum and $(1.8\pm0.5)\times10^{-4}$ from the second 10-sec spectrum. Based on a value of 11.4 sec[9] for the half-life of F^{20} (and therefore of the 1.63-MeV γ rays) the half-life of the 3.3-MeV γ-ray activity is found to be 12.1 ± 4.3 sec. This result establishes

[9] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

with little doubt that the 3.3-MeV γ ray, in fact, belongs to the decay of F^{20}.

Our final result for the F^{20}-branching intensity to the 4.97-MeV state is $(1.7\pm0.3)\times10^{-4}$. The corresponding $\log ft$ value is 6.89 ± 0.08. This agrees with, but is more accurate than, the previously reported value[1] for this branch of 1.7×10^{-4} which gave a $\log ft$ value of 6.9 ± 0.2. As pointed out previously[1] this $\log ft$ value is consistent with a first-forbidden β-ray transition from F^{20}, which has a spin-parity assignment $J^{\pi}=2^{+}$, to the 4.97-MeV state of Ne^{20} which has been established as $J^{\pi}=2^{-}$.

The two time-delayed spectra described above were also examined for evidence of a β-ray transition to the 4248-keV 4^{+} level of Ne^{20}. This state is known[9] to decay by emitting a cascade γ ray of 2614 keV to the 1634-keV first excited state. Unfortunately the cascade γ ray has practically the same energy as the γ ray from thorium room background. In both of the time-delayed spectra the thorium 2614-keV line appeared and its intensity was nearly the same in each, after correcting for small differences in the actual lengths of the time intervals and for differences in the effective values of the analyzer dead time for the two intervals. By taking twice the statistical error in the intensity of the 2614-keV peak as the maximum fraction of that line that could be attributed to the decay of F^{20}, and which could produce a noticeable decay in the line found in the two spectra, a limit of $<1.5\times10^{-4}$ is derived for the F^{20} β-ray branch to the Ne^{20} 4248-keV state. This is a factor of 4 lower than the limit of 6×10^{-4} found earlier[1] and corresponds to $\log ft>7.6$ as compared with the previous lower limit of $\log ft>7.0$.

Energy measurements were made on the 3.3-MeV line by employing the split target technique and by comparing the position of the 3.3-MeV full-energy-loss peak with that of the 2-escape peak of the (4438.91 ± 0.31)-keV[6] γ ray occurring in the decay of B^{12}. Targets of BaF_2 3 mg/cm^2 thick and B^{11} 6 μg/cm^2 thick, each evaporated onto a backing, were mounted side by side and bombarded with a 2.0-MeV beam of deuterons. The fast chopper had to be used for this experiment because of the 20-msec half-life of B^{12}. Both the thicknesses and positions of the targets were chosen so that the 2-escape peak of the 4438.9-keV B^{12} γ ray would be somewhat more intense than the F^{20} line, but not so strong as to result in a significant B^{12}-background contribution in the region of the 3.3-MeV peak. Aluminum and brass absorbers, 17 mm and 2.7 mm thick, respectively, were placed between the target and the 22-cc Ge(Li) detector to stop the energetic β rays from both activities.

Figure 4 shows the results of a total of $\sim$24 h of recording the $F^{20}+B^{12}$ γ-ray spectrum. The (1633.7 ± 0.3)-keV[8] line (not shown) occurred at channel 1882.3, and by using this together with the B^{12} peak the analyzer dispersion was determined. Computer fits to the data of Fig. 4 were made under several different assumptions as to the linewidth and the low-energy tail. Values for the separation of the two peaks differed only slightly for the various fits; one such fit is shown by the solid line in Fig. 4. Our final value for the energy separation between the two peaks is 82.6 ± 0.7 keV. Based on the B^{12} γ-ray energy this leads to a value for the F^{20} γ-ray energy of 3334.3 ± 0.7 keV and thus a level separation of 3334.6 ± 0.7 after correcting for recoil. By adding to this the value of 1633.7 ± 0.3 keV for the excitation energy[8] of the Ne^{20} first excited state, the energy of the 4.97-MeV state is then 4968.3 ± 0.8 keV. This value for the Ne^{20} level is considerably more accurate than the earlier results of 4969 ± 6 keV[9] and 4967 ± 8 keV.[1]

ACKNOWLEDGMENTS

We wish to thank E. K. Warburton for helpful discussions. One of us (DEA) would like to thank S. Gorodetzky and A. Gallmann for a guest appointment at the Institut de Recherches Nucléaires, Strasbourg, France. The Ge(Li) detector used in this work was fabricated at Strasbourg by M. Molinari. We are indebted to J. W. Olness for assistance in making computer fits to some of the data.