hood, the rms charge radius of C^{12} is larger than 2.5 F, which is an improved result over that obtained by Mayer-Berkhout *et al.*[24] In the analysis of the latter authors, a value as small as 2.36 F is still allowed.

The above discussion indicates that in these cases where the properties of the core nuclei are not too well known, an experimental determination of the values of B_Λ would very helpful in determining the structure of the cores. As has been mentioned by Dalitz and Levi-Setti,[36] a possible application of such a technique is to study the properties of core nuclei far off the stability line, of which little is known at the present time.

To make a further test of the idea of using Λ particles as a nuclear probe, we feel that a study of the nucleus O^{16} and the hypernucleus $_{\Lambda}O^{17}$ would be a worthwhile project. In the case of O^{16}, the rms charge radius has already been well determined.[24] Unfortunately, however, the value of B_Λ for $_{\Lambda}O^{17}$ is not yet known. At present, we are making a detailed calculation on these two systems using the same models as those employed in this investigation. If the value of B_Λ should turn out to agree with the experimental value eventually determined and be a sensitive function of the rms charge radius of O^{16}, then we would consider the idea of using Λ particles as a nuclear probe to be a truly useful one and apply it to other more complicated systems.

[36] R. H. Dalitz and R. Levi-Setti, Nuovo Cimento 30, 489 (1963).

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Studies of the Short-Lived Activities C^{15}, F^{17}, O^{19}, F^{20}, and Al^{28}†

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The short-lived activities C^{15}, F^{17}, 0^{19}, F^{20}, and Al^{28} have been studied by bombarding targets with a mechanically chopped Van de Graaff deuteron beam and by measuring the delayed gamma radiations with a lithium-drifted germanium detector. In the decay of C^{15}, weak gamma rays of 8315±6 and 9048±4 keV have been observed which correspond to beta-ray branches to the 8312- and 9052-keV states of N^{15} with log*ft* values of 4.8±0.3 and 3.7±0.3, respectively. In the known beta decay of O^{19} to the 1554-keV level of F^{19}, the energy of this state is found to be 1553.9±1.3 keV, and the measured gamma-ray branching intensities agree with previous results. A weak gamma ray of 3334±8 keV was observed in the beta decay of F^{20}, corresponding to a beta-ray branch to the 4969-keV state of Ne^{20} with $\log ft=6.9\pm0.2$. The energy of the Ne^{20} first excited state was measured as 1632.6±0.8 keV. The gamma ray emitted in the decay of Al^{28} has an energy of 1777.8±0.6 keV. Upper limits are given for other possible beta-ray branches to known states in the decays of the various activities studied.

INTRODUCTION

BECAUSE of its high resolution capabilities, the lithium-drifted germanium Ge(Li) detector has proved to be exceedingly useful in studies of radioactive sources, not only for the accurate measurement of gamma-ray energies and the separation of close-lying gamma-ray lines, but for the detection of weak gamma-ray components. While the first two of these advantages obviously result from good resolution, the last arises because the characteristic peaks (full-energy and escape peaks) occupy very narrow energy intervals and their amplitudes are therefore enhanced (relative to background continua) compared with devices of poorer resolution, such as the NaI(Tl) crystal detector. In favorable cases we have found that even for a Ge(Li) detector with a sensitive volume of 3.6 cm^3 the possibility of detecting weak gamma-ray components of up to 10 MeV can be substantially better than for a 5×5-in. NaI(Tl) detector. It is expected that, when Ge(Li) detectors of 30 to 50 cm^3 volume become more generally available, the situation will be improved even further because of their higher total efficiency and their greater peak-to-total ratios.

During recent years numerous short-lived activities produced by Van de Graaff bombardment have been studied at this laboratory by means of a variety of scintillation spectrometers and an iron-free intermediate-image beta-ray spectrometer. With the advent of the Ge(Li) detector it was felt that previously unobserved and interesting details of some of these decay schemes might be revealed by using this device. An example is the decay of C^{15}, which is one of the principal studies reported in the present paper. This 2.25-sec beta-ray emitter has a decay energy of 9770 keV and it is known[1] to decay via two beta-ray branches, one to the $J^\pi=\frac{1}{2}^-$ ground state of N^{15} (32%; $\log ft=6.0$), and the other to the 5299-keV $J^\pi=\frac{1}{2}^+$ upper member of the 5270–5299-keV doublet (68%; $\log ft=4.1$). Based on $C^{14}(d,p)C^{15}$ stripping results and on the beta-decay

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] D. E. Alburger, A. Gallmann, and D. H. Wilkinson, Phys. Rev. 116, 939 (1959).

information, the spin parity of C^{15} is established[2] as $J^\pi=\frac{1}{2}^+$. In recent work[3] at this laboratory spin-parity information has been obtained on many of the energy levels in N^{15} up to 10-MeV excitation energy. Above the first excited-state doublet at 5.3 MeV there are four excited states of N^{15} having spin-parities of $\frac{1}{2}^+$ or $\frac{3}{2}^+$, namely the levels at 7300, 8312, 8570, and 9052 keV. All of these can be reached energetically in C^{15} decay and could be fed by allowed beta-ray transitions. Information on branches to these states is of particular interest, since independent-particle calculations[4] have been applied to predict the logft values of the C^{15} beta-ray branches to the 7300- and 8312-keV states. In this paper we report on measurements in which the expected beta-ray transitions to two of the N^{15} levels, namely those at 8312 and 9052 keV, have been observed.

Another case in which a previously undetected beta-ray branch has been found in the present work is the beta decay of F^{20}. This activity has a half-life of 11.4 sec and a total decay energy of 7028 keV. It has been reported[5] that the decay proceeds entirely by beta-ray emission to the 1633-keV $J^\pi=2^+$ first excited state of Ne^{20} (logft=4.99), and that the possible beta-ray branches to the ground state and to the 4969-keV level of Ne^{20} have log$ft\gtrsim 9$ and log$ft>6.5$, respectively. F^{20} has been assigned[6] a spin-parity of $J^\pi=2^+$.

Because of its possible role in the stellar formation of Ne^{20} via the $O^{16}(\alpha,\gamma)Ne^{20}$ reaction, the 4969-keV level of Ne^{20} has been studied thoroughly at Chalk River in a series of experiments[7] which have established $J^\pi=2^-$ for this level. Since the state is of "unnatural" parity, it cannot be involved in the stellar formation of Ne^{20} nor can it decay to $O^{16}+\alpha$. However, from the point of view of F^{20} decay, the 4969-keV level could be fed by a first-forbidden beta-ray branch with an end-point energy of 2.06 MeV and therefore the subsequent gamma radiation might be observable.

F^{17} has a half-life of 66 sec and decays[5,6] by positron emission to the ground state of O^{17}. The probable spin parity of F^{17} is $J^\pi=\frac{5}{2}^+$ and the O^{17} ground state has $J^\pi=\frac{5}{2}^+$. The decay energy of F^{17} is 2767 keV, the decay to the O^{17} ground state having logft=3.38. There is only one known excited state of O^{17} to which another positron branch could occur, namely the $J^\pi=\frac{1}{2}^+$ state at 871 keV. A previous upper limit[5] of 1% has been placed on a possible positron branch to the 871-keV state.

[2] D. E. Alburger, C. Chasman, K. W. Jones, and R. A. Ristinen, Phys. Rev. **136**, B913 (1964) summarize the evidence.

[3] E. K. Warburton, J. W. Olness, and D. E. Alburger, Phys. Rev. **140**, B1202 (1965).

[4] See Ref. 1, Table IV.

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

[6] T. Lauritsen and F. Ajzenberg-Selove, *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1962), Sets 5 and 6.

[7] H. E. Gove, A. E. Litherland, and M. A. Clark, Nucl. Phys. **41**, 448 (1963).

O^{19} is a 29-sec half-life beta-ray emitter which is known[1] to decay with a 41.5% branch to the 197-keV $J^\pi=\frac{5}{2}^+$ second-excited state of F^{19} (logft=5.45) and with a 58.5% branch to the 1554-keV $J^\pi=\frac{3}{2}^+$ fifth-excited state (logft=4.51). Recently a further investigation of this activity by Olness and Wilkinson[8] has revealed a 0.16% beta-ray branch to the known state of F^{19} at 4390 keV (logft=3.54). In addition they made a study of the gamma-ray branching from the 1554-keV state. Three gamma-ray transitions were observed, but since the lines were not well resolved in their NaI(Tl) spectra, they used computer techniques to extract the relative intensities of the lines. It was felt that it would be useful to check these branching ratios by measuring the O^{19} gamma-ray spectrum at a considerably higher resolution.

The study of Al^{28} decay was made for the purpose of accurately determining the energy of the emitted gamma ray. Al^{28} has a half-life of 2.28 min and is known to decay[9] almost entirely to the $J^\pi=2^+$ first excited state of Si^{28}, whose energy is given[9] as 1772±5 keV. The second excited state of Si^{28} is at 4614±6 keV and it is known to have $J^\pi=4^+$. Since Al^{28} has $J^\pi=3^+$, an allowed beta decay should proceed to the 4614-keV state, but its end-point energy would be only 26±7 keV and thus the detection of this branch was considered to be well outside the capabilities of the present techniques.

EXPERIMENTAL PROCEDURES AND METHODS OF ANALYSIS

Measurements on the gamma-ray spectra were made with two different Ge(Li) detectors having sensitive volumes of about 3.6 cm^3 (~6 cm^2×6 mm deep). Initially their resolutions were about 6 keV for the 661-keV gamma rays of Cs^{137}, although some of the work was done when only one detector was available and its resolution had deteriorated to 10 keV at this energy. The amplifier output was fed to a 16 384-channel pulse-height analyzer and generally the data were displayed in one of the 1024-channel sections.

The activities to be studied were produced by Van de Graaff bombardment of various targets using a mechanical beam chopper and timing system described previously.[10] This device operates on a 17-msec cycle, in which the beam irradiation time is 3 msec and the delayed counting interval is 12 msec. By means of a gating circuit only those pulses occurring during the 12-msec interval are stored in the analyzer.

Tests were made of the line shape for various delayed counting rates. It had previously been observed with radioactive sources that the shapes of the lines began to change and the resolution became worse at rates higher than about 2000/sec. This has usually been attributed

[8] J. W. Olness and D. H. Wilkinson, Phys. Rev. **141**, 966 (1966).

[9] P. M. Endt and C. van der Leun, Nucl. Phys. **34**, 1 (1962).

[10] D. E. Alburger, Phys. Rev. **131**, 1624 (1963).

to pulse pile-up effects. Under the conditions of these chopped-beam experiments, the linewidths and line shapes, and their dependence on the delayed counting rate seemed to be essentially the same as in tests with long-lived radioactive sources. Since the intensity of prompt gamma rays and neutrons from the target during the 3-msec irradiation interval is probably one or two orders of magnitude greater than the rate of gamma-ray emission during the 12-msec counting interval, it is concluded that the detecting system recovers fully within 1 msec from any deleterious effects produced by the high radiation level during the beam-on period.

Several methods were used for deriving the energies of the gamma rays observed. In some cases the peak positions were compared with those of standard calibration sources by using linear interpolation or extrapolation. In other cases, such as for large extrapolations to high energies, a precision pulser provided reference lines which were used to establish an accurate calibration curve following techniques described previously.[2]

Relative intensities of low-energy gamma rays were derived from the intensities of full-energy-loss peaks by making efficiency corrections based on data published by Ewan and Tavendale.[11] Their curve (Fig. 14b in Ref. 11) of full-energy peak efficiency-versus-gamma-ray energy for a 4-cm^3 detector was considered to be closely applicable to our 3.6-cm^3 detector.

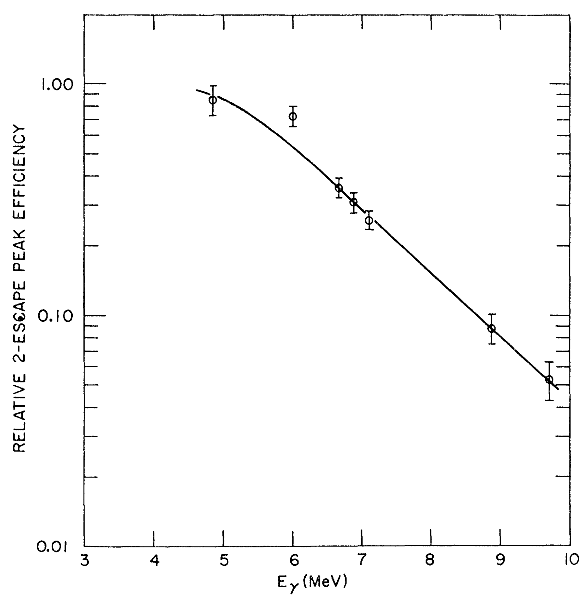

FIG. 1. Relative 2-escape peak efficiency-versus-gamma-ray energy for a Ge(Li) detector having a sensitive volume of 3.6 cm^3. The data were derived from measurements on the $Cr^{53}(n,\gamma)Cr^{54}$ reaction using thermal neutrons. The indicated errors are those on the intensities of the capture γ-rays, as reported in the literature.

[11] G. T. Ewan and A. J. Tavendale, Can. J. Phys. **42**, 2286 (1964).

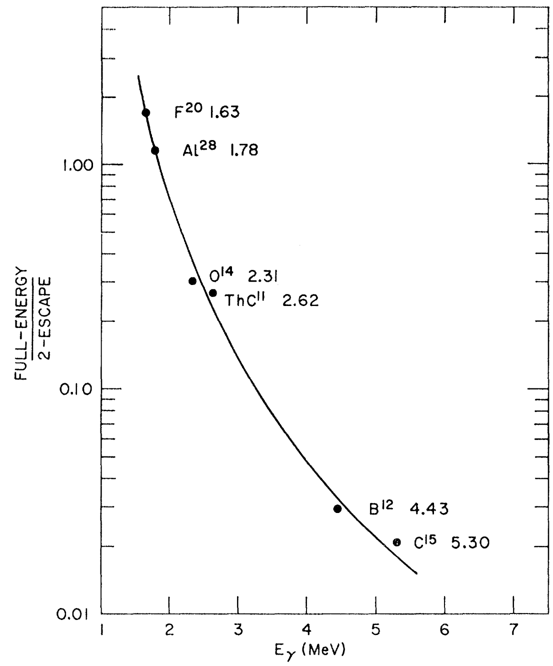

FIG. 2. Ratio of the intensities of the full-energy peak to the two-escape peak-versus-gamma-ray energy for a Ge(Li) detector having a sensitive volume of 3.6 cm^3.

For high-energy gamma rays, such as those observed in C^{15} decay, the efficiency function for the two-escape peak versus gamma-ray energy had to be known. Ewan and Tavendale[11] present such data for a 2.5 cm^2×3.5 mm deep detector (sensitive volume ~0.9 cm^3), but it was not known if their efficiency curve could be applied to our 3.6-cm^3 detector.

In order to determine the 2-escape efficiency function for our detector the thermal neutron-capture gamma-ray spectrum from the $Cr^{53}(n,\gamma)Cr^{54}$ reaction was measured at the Brookhaven reactor. This reaction has been studied by Kinsey and Bartholomew[12] and by Groshev *et al.*[13] using magnetic spectrometers to determine the gamma-ray energies and relative intensities. The spectrum contains strong gamma-ray lines of up to 9.72 MeV. A sample of chromium enriched in Cr^{53} was exposed to a collimated beam of thermal neutrons and the Ge(Li) detector was placed at an angle of 90° to the beam. The detector was suitably shielded from the reactor and from the neutron beam catcher.

In the pulse-height spectrum from the Ge(Li) detector the 2-escape peaks corresponding to seven of the strong $Cr^{53}(n,\gamma)Cr^{54}$ capture gamma-ray transitions between 4.83 and 9.72 MeV were readily identified. (A relatively strong gamma ray of 7.73 MeV was attributed to neutron capture in the aluminum can that held the

[12] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).

[13] L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, *Atlas of γ-Ray Spectra from Radiative Capture of Thermal Neutrons*, translated by J. B. Sykes (Pergamon Press, Inc., New York, 1959).

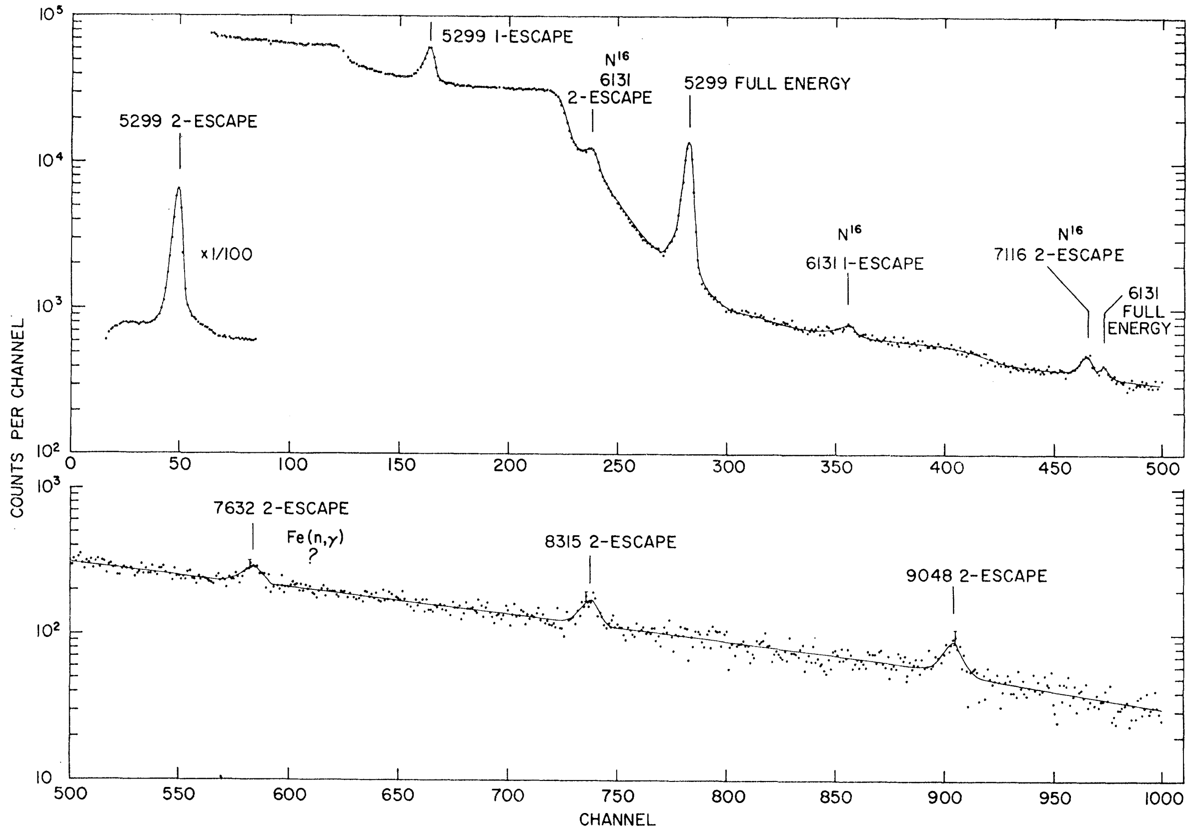

FIG. 3. Gamma-ray spectrum from the decay of C^{15} recorded in a run of 70-h duration. Transition energies are in keV.

Cr^{53} sample.) The net intensities of the seven 2-escape peaks from the Cr^{54} gamma rays were corrected according to the averages of the relative gamma-ray intensities given by Kinsey and Bartholomew[12] and by Groshev *et al.*[13]

The curve of relative 2-escape peak efficiency versus gamma-ray energy derived in this way is shown in Fig. 1. A comparison of Fig. 1 with the data of Ewan and Tavendale for their 0.9 cm^3 detector (Fig. 22 of Ref. 11) shows a rather close agreement in the relative efficiencies over the energy range from 5 to 10 MeV.

Whereas Fig. 1 could be applied to the C^{15} data, it could not be used in the case of F^{20}, since it was necessary to find the relative 2-escape-peak efficiencies for gamma rays of 1.63 and 3.33 MeV. Ewan and Tavendale's 2-escape efficiency curve[11] shows that for gamma-ray energies up to about 3 MeV the experimental efficiency closely follows the shape of the pair-production cross section, corrected for the absorption of one annihilation quantum. In view of this it was felt that Ewan and Tavendale's experimental efficiency curve could be used with relatively little error in correcting our data on the two-escape peaks of the 1.63 and 3.33-MeV gamma rays in F^{20} decay.

Since one of the purposes of the present work was to search for weak gamma-ray components it was felt desirable to have a general guide as to which of the characteristic peaks it would be most profitable to search for. The one-escape peak is always much smaller than the two-escape peak for a 3.6-cm^3 detector and thus it is usually necessary to consider only the full-energy-loss and two-escape peaks. Figure 2 shows a plot of the ratio of the full-energy-loss peak intensity to the 2-escape peak intensity-versus-gamma-ray energy, based on data taken with our 3.6-cm^3 Ge(Li) detector. At about 1.8 MeV the intensities of these peaks are equal. The ratio decreases rapidly with increasing gamma-ray energy and it is down to 0.1 at about 3.3 MeV. Thus, in most cases the 2-escape peak will be the most useful one to observe at gamma-ray energies above 2.5 MeV and above 5 MeV the 2-escape peak may be the only one visible, if the background is high and if the transition is weak.

EXPERIMENTAL RESULTS AND DISCUSSION

C^{15}

The C^{15} activity was formed in the $C^{14}(d,p)C^{15}$ reaction by bombarding a 0.7-mg/cm^2 thick carbon target, containing 80% C^{14} with a 2.7-MeV deuteron beam. Graphite and lead absorbers shielded the detector from high-energy beta rays and reduced the relative intensities of low-energy gamma rays. A biased amplifier was used and the gain conditions were adjusted so that the 2-escape peaks of gamma rays between 5.0 and 9.5 MeV would be recorded over the 1024 channels of the pulse-height analyzer.

Figure 3 shows the data obtained in a 70-h run at a beam current of 0.095 μA. The upper half of the figure contains part of the Compton distribution and the three characteristic peaks of the 5299-keV gamma ray. Since the analyzer capacity is 10^5 counts per channel, the 5299-keV 2-escape peak spilled over a number of times during the long run. Hence the 5299-keV 2-escape peak in Fig. 3 was taken from a shorter run normalized to the intensity of the 5299-keV full-energy-loss peak.

Four weak lines also appear in the upper part of Fig. 3. With respect to their energies, as checked against a calibrated pulser, and to their relative intensities these lines are characteristic of the 6131- and 7116-keV gamma rays in the decay of N^{16} (as designated in the figure). The presence of the N^{16} activity can be understood from the fact that the C^{14} target was attached to a Ta holder on the back of which was a deposit of TiN^{15}. This target arrangement had been used for earlier measurements[2] of the energy of the C^{15} gamma ray. N^{16} would be produced by the $N^{15}(d,p)N^{16}$ reaction if a small TiN^{15} contamination had gotten onto the C^{14} side of the target holder in the region of the beam spot. An alternative explanation would be that the neutron flux from the (d,n) reactions on the $C^{14,12}$ target might be producing the observed N^{16} activity in the TiN^{15} deposit on the rear side of the target holder via the $N^{15}(n,\gamma)N^{16}$ reaction.

In the lower half of Fig. 3 there are three distinct peaks rising above a background which decreases exponentially with energy. Because of the absence of detectable associated lines separated by 511 or 1022 keV from any of these peaks, and in view of the data of Fig. 2, these three lines may be assigned definitely as 2-escape peaks. In order to derive their energies a precision pulser was used to establish the shape of the calibration curve between 4 and 8.5 MeV. A computer polynomial fit was made to the peak channel numbers of the pulser lines and the energy constants of the resulting calibration curve were found by fitting the curve to the channel numbers at the peaks of the 5299-keV 2-escape and full-energy-loss lines. From the channel numbers at the peaks of the three lines in the lower part of Fig. 3, their energies were then calculated. The corresponding gamma-ray energies are as follows:

$$7632\pm4 \text{ keV},$$
$$8315\pm6 \text{ keV},$$
$$9048\pm4 \text{ keV}.$$

On the basis of their energies, two of these transitions may be associated with energy levels in N^{15}. According to a previous investigation,[3] the two levels in question are those having energies of 8312 ± 2.0 and 9052 ± 4.6 keV, for both of which the spin-parities are assigned as $J^\pi=\frac{1}{2}^+$ or $\frac{3}{2}^+$. The 8312-keV level de-excites $(78\pm3)\%$ by a ground-state transition and the 9052-keV level decays $(92\pm3)\%$ by a ground-state branch. Since C^{15} has $J^\pi=\frac{1}{2}^+$, it is to be expected that allowed beta decays should populate these two levels and that the predominant ground-state transitions might be observable.

The 7632-keV gamma rays, on the other hand, cannot be associated with known energy levels in N^{15} that would be populated in C^{15} decay. Furthermore, there does not appear to be any other known radioactivity that could be produced in the target and which would emit gamma rays of this energy. Various sources of background radiation may be considered. During the 12-msec delayed counting interval the beam is intercepted by the chopper rotor, which is located $\sim$15 ft from the target and detector. Gamma rays are produced by deuteron reactions on carbon deposits and occluded oxygen on the chopper rotor, but it would be difficult to understand the direct production of 7632-keV gamma rays at the chopper. However, a copious yield of neutrons is also produced at the chopper by the $C^{12}(d,n)N^{13}$ reaction. These neutrons slow down and they may be captured in materials close to the detector, resulting in a gamma-ray background. Most of the material in the target room consists of the concrete in the walls and the iron in the heavy target platform. From a search of the data on neutron-capture gamma-ray spectra compiled by Bartholomew and Higgs,[14] it was found that a gamma ray of 7639 ± 4 keV is emitted in the capture of thermal neutrons by iron and that this transition is 5 times stronger than any of the other lines in the spectrum. The agreement between the energy of the gamma-ray observed in the C^{15} run and that known to occur in the neutron capture by iron suggests that this is the most reasonable explanation for the origin of this line.

A test as to the background nature of the 7632-keV gamma ray was made by inserting a blank Ta target holder and then running with all other conditions the same as for the C^{15} experiment. The spectrum obtained in a 14-h run showed clear evidence for the 7632-keV 2-escape peak and there were no other lines visible above the background. We therefore assign the 7632-keV gamma-ray as a background line which probably originates from the iron in the room.

Although it is most reasonable to attribute the 8315- and 9048-keV gamma rays to the decay of C^{15}, the possibility that these gamma rays could be explained in some other way was considered. In particular, the capture of neutrons in the liquid nitrogen that cools the Ge(Li) detector can lead to these same states in N^{15}. This possibility is almost certainly ruled out by data on the relative intensities of the neutron capture gamma rays from nitrogen. In the region of interest the gamma rays (in MeV) and their absolute intensities (in percent)

[14] G. A. Bartholomew and L. A. Higgs, Atomic Energy of Canada Ltd. Report CRGP-784 1958 (unpublished).

have been reported[14] as follows:

9.152±0.010	1
9.03 ±0.04	0.2
8.54 ±0.04	0.2
8.313±0.013	4
7.305±0.012	9
6.323±0.008	17 .

The 9.03-MeV gamma ray is presumably that from the 9052-keV state. Thus the intensity ratio $I_{8.313}/I_{9.03}\cong 20$ in the neutron capture spectrum is completely inconsistent with the relative intensities of the two lines in Fig. 3 and, furthermore, we see no evidence for the stronger gamma rays of 7.305 and 6.323 MeV that occur in the neutron-capture spectrum from nitrogen.

Neutron-capture gamma rays could be produced, not only by neutrons generated at the chopper, but by neutrons from the target which were eventually captured at a time later than the opening of the counting gate (1 msec after the end of the beam burst). In order to reduce this type of effect, as well as to check that the 8315- and 9048-keV gamma rays were indeed coming from the target, the delay between the end of the beam burst and the opening of the counting gate was increased from 1 msec to 5 msec and the length of the gate was shortened from 12 msec to 8 msec. A run of several hours showed, although with poor statistics, that the three high-energy gamma rays were still present with approximately the same intensities relative to the 5299-keV part of the spectrum as in Fig. 3. We therefore conclude that the 8315- and 9048-keV gamma rays result from the beta decay of C^{15} to the known N^{15} levels.

The beta-ray branching ratios were calculated by first finding the intensities of the 8315- and 9048-keV 2-escape peaks relative to the 5299-keV 2-escape peak and correcting these ratios for 2-escape peak efficiencies according to Fig. 1. The ratios of gamma-ray intensities thus obtained were then corrected for the known gamma-ray branching ratios from these two levels and for the known fractional beta-ray branch to the 5299-keV level. The resulting beta-ray branching intensities and log*ft* values are listed in Table I.

TABLE I. Beta-ray branching intensities and log*ft* values for the decay of C^{15} to the ground state of N^{15} and to all levels of N^{15} below 9.1 MeV known to have $J^\pi=\frac{1}{2}^+$ or $\frac{3}{2}^+$.

Level in N^{15} (keV)	Fractional beta-ray branch	log*ft* (exp.)	log*ft* (theor.)[a]
0	0.32[b]	6.0	5.8
5299	0.68[b]	4.1	4.80
7300	$<4.4\times10^{-4}$ [c]	>6.1	6.49
8312	1.02×10^{-3} [c]	4.8±0.3	4.51
8570	$<2.5\times10^{-3}$ [c]	>4.0	
9052	8.7×10^{-4} [c]	3.7±0.3	

[a] See Ref. 1, Table IV. [b] See Ref. 5. [c] Present work.

Ground-state gamma-ray transitions corresponding to the other two possible allowed beta-decay branches, namely those to the N^{15} states at 7300 and 8570 keV, do not produce observable 2-escape peaks in Fig. 3. These levels are known[3] to decay (98±1)% and (32±4)%, respectively, by ground-state transitions. Following the procedures described above, upper limits on the beta-ray branches and lower limits for the log*ft* values of these two branches were calculated and they are included in Table I.

Also presented in Table I are the theoretical predictions of the log*ft* values of C^{15} beta-ray branches summarized previously.[4] Of the two new beta-ray branches reported in the present work, the log*ft* value of 4.8±0.3 for the branch to the 8312-keV level is in agreement with theoretical prediction of 4.51. The previous experimental lower limit[1] of log*ft*≥5.0, when corrected for the gamma-ray branching ratio, would correspond to log*ft*≥4.9, which is not inconsistent with the present experimental result. There is to our knowledge no theoretical calculation for the beta-ray branch to the 9052-keV level with which to compare the experimental result log*ft*=3.7±0.3.

Our limit of log*ft*>6.1 for the beta-ray branch to the 7300-keV level is not appreciably different from the previous limit[1] log*ft*>6.0 and it does not conflict with the theoretically predicted value of 6.49. In the case of the beta-ray branch to the 8570-keV level, the experimental limit of log*ft*>4.0 is reasonable for an allowed beta-ray transition, but again, there is no theoretical calculation for comparison.

Further experimental searches for the 7300- and 8570-keV gamma rays would probably be useful. It should be pointed out that the widths of the high-energy lines in the lower half of Fig. 3 are ~30 keV (full width at half-maximum). Deterioration of the detector accounted for the greatest contribution to the poor resolution and it is very probable that a high-resolution detector, even one of the same sensitive volume as used here, combined with a gain-stabilized amplifying system and a pulse-height analyzer with more channels would have resulted in substantially superior data. However, it is felt that the use of a Ge(Li) detector, having a much larger sensitive volume, would make the most significant improvement in future work of this type on the decay scheme of C^{15}. It would also be desirable to make further theoretical calculations of log*ft* values in C^{15} decay, especially for the beta-ray branches to the 8570- and 9052-keV levels of N^{15}.

F^{17}

For the F^{17} experiments, a thick target of PbO_2 was bombarded with a 0.03-μA beam of 3-MeV deuterons to form the activity via the $O^{16}(d,n)F^{17}$ reaction. The resulting delayed gamma-ray spectrum exhibited only the full-energy-loss peak and Compton-electron distribution of annihilation radiation associated with the positron decay of F^{17} to the ground state of O^{17}. In order to establish the expected pulse height of a possible 871-keV line, the beam intensity was reduced and the analyzer was self-gated so that the total (prompt plus delayed) gamma-ray spectrum was recorded. The prompt spectrum contained the 871-keV line from the $O^{16}(d,p)O^{17}$ reaction and just below the 511-keV annihilation line there was a peak at 495 keV due to the gamma-ray decay of the first excited state of F^{17} resulting from the $O^{16}(d,n)F^{17}$ reaction.

A search was made for the 871-keV line in the F^{17} delayed spectrum at the position where it had occurred in the prompt spectrum. In the delayed spectrum the background counting level at the 871-keV position was lower than the amplitude of the 511-keV full-energy-loss peak by a factor of 1000, but no peak was observed. By using the relative detector efficiencies for the full-energy-loss peaks of 511- and 871-keV gamma rays, and by correcting for absorption and for the two gamma rays in positron annihilation, an upper limit of 6×10^{-4} per decay is placed on the positron branch of F^{17} to the 871-keV first excited state of O^{17}. This is to be compared with a previous upper limit[5] of 1%. The present result corresponds to $\log ft > 5.4$, which is reasonable since the positron emission from N^{17} ($J^{\pi}=\frac{5}{2}^{+}$) to the 871-keV state of O^{17} ($J^{\pi}=\frac{1}{2}^{+}$) is forbidden by the two units of spin change.

O^{19}

A gas target of oxygen enriched to 99.7% O^{18} was bombarded with a 3-MeV deuteron beam to form the O^{19} activity via the $O^{18}(d,p)O^{19}$ reaction. Figure 4 shows that portion of the delayed gamma-ray spectrum which includes the full-energy-loss peaks of the three transitions from the 1554-keV state of F^{19} populated in the beta decay of O^{19}.

Energy values of the three lines that occur in Fig. 4 were obtained in another run taken when a source of Co^{60} was superposed. The energies of the Co^{60} gamma rays are known[11] with very high accuracy, i.e., 1173.226 $\pm$0.040 keV and 1332.48$\pm$0.05 keV. The latter differs by only $\sim$24 keV from the energy of the strongest line in Fig. 4. By using an energy-versus-pulse-height scale derived from the Co^{60} peaks, the strongest line in Fig. 4 is found to have an energy of 1356.9$\pm$1.3 keV. Since this line results from a cascade transition to the (197.0$\pm$0.6)-keV[6] state of F^{19}, the energy of the upper level is 1553.9$\pm$1.4 keV. Independent values for the level energy were obtained from the energies of the other two O^{19} lines, in the first case by adding the (109.87$\pm$0.04)-keV[6] energy of the first excited state of F^{19}. The results are 1553.6$\pm$1.5 keV and 1554.4$\pm$1.5 keV, respectively, for the F^{19} state. A value of 1553.9$\pm$1.3 keV is obtained as the weighted average of the three measurements. The energy of this state has been listed[5] previously as 1556$\pm$3 keV.

In order to find the gamma-ray branching intensities, the net areas under the peaks in Fig. 4 were corrected for detector efficiency and in the case of the 1554-keV line a correction was made for summing effects. Almost all of the summing contribution results from the $1554\rightarrow197\rightarrow0$ cascade. In order to calculate this contribution the total efficiency of our detector for 197-keV gamma rays was derived, based on efficiencies calculated by Hotz *et al.*[15] This was multiplied by a peak-to-total ratio, making use of various data from spectra taken at this laboratory. The resulting absolute peak efficiency, corrected for absorption in the wall of the gas target chamber, gave a summing contribution which amounted to $\frac{1}{3}$ of the intensity of the 1554-keV peak in Fig. 4. The gamma-ray branching intensities from the 1554-keV state derived from the corrected data are given in Table II. The large error in the ground-state branch results from the errors in the calculation of the summing contribution, as discussed above. The present results are in excellent agreement with those of Olness and Wilkinson,[8] given in the third column of Table II.

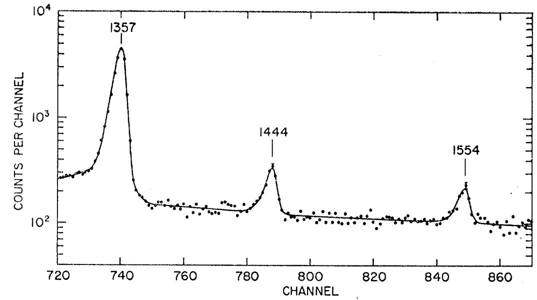

FIG. 4. Full-energy-loss peaks of the three gamma-ray branches from the 1554-keV state of F^{19} following the beta decay of O^{19}. Transition energies are given to the nearest keV.

In a run taken with lower amplifier gain, the 2-escape peak of the 4190-keV gamma ray from the 4390-keV state of F^{19}, previously found by Olness and Wilkinson,[8] was observed, but since the line was very weak no intensity calculations were attempted.

F^{20}

F^{20} was formed in the $F^{19}(d,p)F^{20}$ reaction by bombarding a BaF_2 target several mg/cm² thick with a 0.02-μA beam of deuterons at an energy of 2.0 MeV.

TABLE II. Gamma-ray branching intensities from the 1554-keV state of F^{19} as observed in the beta decay of O^{19}.

Transition (initial and final level, keV)	Present work % branch	Olness and Wilkinson (Ref. 8)
$1554\rightarrow197$	92.7$\pm$1.1	92.4$\pm$0.8
$1554\rightarrow110$	5.0$\pm$0.5	5.2$\pm$0.7
$1554\rightarrow0$	2.2$\pm$1.0	2.4$\pm$0.5

[15] H. P. Hotz, J. M. Mathieson, and J. P. Hurley, U. S. Naval Radiological Defense Laboratory Report USNRDL-TR-817, 1965 (unpublished).

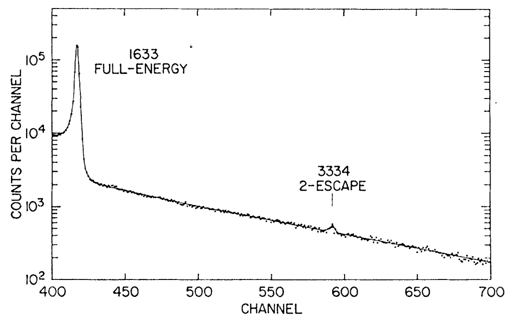

FIG. 5. Gamma-ray spectrum from the decay of F^{20}. Transition energies are in keV.

The energy of the 1633-keV gamma ray was determined by recording the F^{20} spectrum when sources of Na^{22} and ThC'' were superposed. These latter activities emit gamma rays of 1274.44±0.10 keV[16] and 2614.47±0.10 keV,[11] respectively. The 2-escape peak of the ThC'' gamma ray is about 40 keV below the energy of the full-energy-loss peak of the 1633-keV F^{20} gamma ray. By using an energy scale based on the calibration lines, the energy of the F^{20} gamma ray, and thus the first excited state of Ne^{20}, is found to be 1632.6±0.8 keV. This compares with a previously listed value[5] of 1632±4 keV.

Figure 5 shows the results of an 18-h run on the F^{20} gamma-ray spectrum. In the energy region above the 1633-keV full-energy-loss peak one weak line appears above the sloping background continuum. Of the three possible origins of this line (full energy, 1 escape, or 2 escape), the possibility of its assignment as a 1-escape peak due to a gamma ray of about 2.8 MeV can be eliminated because of the absence of a corresponding and much stronger 2-escape line at about channel 460 in Fig. 5. If it were a full-energy-loss peak, the gamma-ray would have an energy of about 2.31 MeV. As an aid in this analysis, the spectrum of O^{14}, formed in the $C^{12}(He^3,n)O^{14}$ reaction, was studied, since O^{14} emits gamma rays of 2.31 MeV. From the relative intensities of the peaks in the O^{14} gamma-ray spectrum, it was found that, if the weak line in Fig. 5 were a full-energy-loss peak, neither the one-escape peak, near channel 460, nor the 2-escape peak, near channel 328, could be seen above the statistical errors of the points in those two regions. However, in this case there would be a broad Compton peak at about channel 522 in Fig. 5 that would be readily apparent as a rise above the exponentially decreasing background continuum. It is therefore concluded that the weak line in Fig. 5 is a 2-escape peak due to a gamma ray of about 3.3 MeV. According to Fig. 2 the corresponding full-energy-loss peak would then be ~10 times weaker than the 2-escape peak, and thus could not be seen in this run above the statistical errors of the background points in the vicinity of channel 724 (off the end of Fig. 5).

[16] C. Chasman and R. A. Ristinen (private communication).

Based on an energy calibration curve derived from the F^{20} 1633-keV line and the full-energy-loss peak due to the 2614.5-keV[11] gamma ray of ThC'', measured in a separate run, the gamma-ray energy corresponding to the weak line in Fig. 5 is 3334±8 keV. If this is added to the energy of the Ne^{20} first excited state, the corresponding energy level value is 4967±8 keV. This agrees very well with the energy 4969±6 keV given[5] previously for the Ne^{20} state. Since this level is known[5] to decay >95% by a cascade transition to the 1633-keV level, it is very probable that the weak peak in Fig. 5 can, in fact, be assigned to the decay of the Ne^{20} state.

In order to derive the logft value for the F^{20} beta-ray branch to the 4969-keV state, the ratio of the net area under the 3334-keV 2-escape peak in Fig. 5 to the net area under the 2-escape peak of the 1633-keV gamma ray (not shown in Fig. 5) was measured and found to be 9.8×10^{-4}. This was multiplied by the ratio of the detector efficiencies for the two energies and a gamma-ray intensity ratio $I_{3334}/I_{1633}=1.7\times10^{-4}$ was obtained. If our interpretation of the data is correct, the above gamma-ray intensity ratio also represents the fractional beta-ray branching of F^{20} to the 4969-keV state of Ne^{20}. The corresponding logft value is 6.9±0.2, which compares with a previous lower limit[5] of 6.5. Since F^{20} is very probably $J^\pi=2^+$, and since the 4969-keV state has been shown to have $J^\pi=2^-$, the beta-ray transition is forbidden by the parity change and thus the measured logft value is quite reasonable.

Other possible beta-ray branches of F^{20} could take place to the 4248- and 5631-keV states of Ne^{20} which have been assigned[6] spin-parities of $J^\pi=4^+$ and 3^-, respectively, and are therefore both of "natural" parity. The 5631-keV level is unbound and is known to decay predominantly by alpha-particle emission to the ground state of O^{16}. The 4248-keV level of Ne^{20} is bound and is known[5] to decay >90% to the 1633-keV first excited state. The cascade gamma ray would therefore have an energy of 2615 keV. For such a transition the 2-escape peak would occur on the low-energy tail of the 1633-keV full-energy-loss peak, whereas its full-energy-loss peak would be at about channel 672 in Fig. 5. From the upper limit on the intensity of such a full-energy-loss peak an upper limit on the intensity of the corresponding 2-escape peak was inferred by using the ratio data in Fig. 2. Efficiency corrections were then made (as in the case of the 3334-keV 2-escape peak) and an upper limit of 6×10^{-4} was derived for the fractional branching. This corresponds to logft>7.0 for the beta-ray branching of F^{20} to the 4248-keV level of Ne^{20}.

Al^{28}

This activity was formed in the $Al^{27}(d,p)Al^{28}$ reaction by bombarding an aluminum foil with 2.5-MeV deuterons. In order to determine the energy of the gamma ray emitted in Al^{28} decay it was found convenient to superpose a source of Bi^{207}. The energies of the

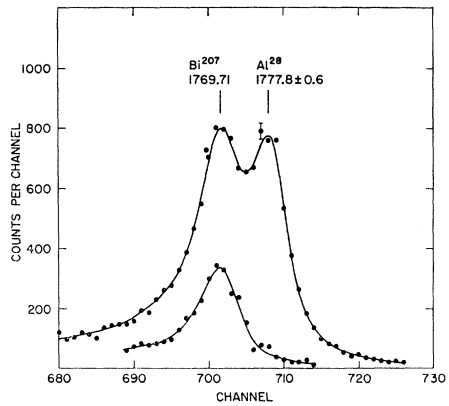

FIG. 6. Upper curve—full-energy-loss peaks in the gamma-ray spectrum from the decay of Al^{28} with a source of Bi^{207} superposed. Energies are in keV. Lower curve—shorter run on Bi^{207} alone after removal of the beam and decay of the Al^{28} activity.

three strongest gamma rays from Bi^{207} have recently been measured by Brady *et al.*,[17] who report energy values of 569.62±0.06, 1063.44±0.09, and 1769.71 ±0.13 keV. A preliminary run showed that the highest energy Bi^{207} gamma ray was only about 8 keV below the energy of the Al^{28} gamma ray. Since the Al^{28} and Bi^{207} peaks were not completely separated in the Ge(Li) spectrum, the final run was made after adjusting the beam intensity so that the counting rates of the two lines were very nearly the same. The upper curve in Fig. 6 shows a portion of the resulting spectrum. For comparison the lower curve in Fig. 6 is a shorter run on the Bi^{207} activity made after the beam had been turned off and after the Al^{28} activity had been allowed to decay. The number of channels between the two peaks in the $Bi^{207}+Al^{28}$ spectrum in Fig. 6 was multiplied by the dispersion in keV per channel, as determined from the Bi^{207} 1063.44- and 1769.71-keV lines. The resulting energy of the Al^{28} gamma ray, and thus the first excited state of Si^{28} is 1777.8±0.6 keV, which compares with a previously listed energy value of 1772±5 keV.

[17] F. P. Brady, N. F. Peek, and R. A. Warner, Nucl. Phys. **66**, 365 (1965).

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