Gamma-Rays from Deuteron Bombardment of B^{10}, B^{11}, N^{14}, and F^{19}

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A pair spectrometer has been used to analyze the high energy gamma-ray spectra produced by bombarding thick targets of natural boron, enriched boron, nitrogen, and fluorine with 1.56-Mev deuterons from a Van de Graaff generator. The $B^{10}+d$ spectrum shows gamma-rays of energy 4.52±0.10, 6.71±0.13, and 9.04±0.18 Mev; the spectrum from $B^{11}+d$, partially masked by the strong $B^{10}+d$ gamma-rays, shows a single 4.5±0.1-Mev gamma-ray. The nitrogen target produced strong gamma-rays of energy 5.33±0.11, 7.40±0.15, and 8.46±0.17 Mev, with some indication of unresolved lines at 4.4 and 6.4 Mev. The $F^{19}+d$ spectrum shows weak high energy gamma-rays, not previously observed, of energy 8.1±0.4, 9.3±0.3, and 11.5±0.4 Mev; a level in Ne^{20} at 11.5±0.4 Mev is indicated. In any of these spectra lower energy gamma-rays may be present though undetected, because of the large variation of spectrometer sensitivity with energy. Absolute yield values are estimated for each of these gamma-rays.

I. INTRODUCTION

HIGH energy gamma-ray spectra produced by a number of light-element nuclear reactions have not been fully clarified; the earlier cloud-chamber and absorption techniques did not, in general, have the resolution and statistical accuracy needed to resolve these spectra fully. The reasonably high counting rates and good resolution now available in pair spectrometers have made reinvestigations desirable.

The investigation reported here was undertaken with a pair spectrometer designed specifically for high counting rate, at the expense of some resolution. This spectrometer has been previously used with success on the low intensity gamma-rays produced by a polonium-beryllium mixture.[1] The reactions investigated were produced by deuteron bombardment of thick targets of natural boron, enriched boron, nitrogen, and fluorine.

The gamma-rays from $B+d$ have been analyzed by Gaerttner, Fowler, and Lauritsen,[2] and by Halpern and Crane,[3] both groups using cloud chambers and the natural isotopic mixture of B^{10} and B^{11}; Hudspeth and Swann[4] have investigated the low energy gamma-rays by coincidence absorption methods. Very recently, Rutherglen[5,6] has observed the gamma-ray spectrum using separated isotopes and a pair spectrometer, obtaining results similar to those reported here.

The $N^{14}+d$ gamma-ray spectrum has been analyzed only by means of cloud-chambers; results have been reported by Gaerttner and Pardue,[7] and by Crane, Halpern, and Oleson.[8]

The only report on the $F^{19}+d$ high energy gamma-ray spectrum seems to be that of Bennett, Bonner, and Watt,[9] who used absorption methods. Jelley[10] and Littauer[11] have published investigations of the low energy gamma-rays from the beta-disintegration of F^{20}, produced by this reaction.

In addition to these direct measurements of the gamma-ray spectra there is much indirect information on the gamma-ray energies from Q-value measurements and from α-γ, β-γ, and p-γ coincidence measurements. Many references to this literature may be found in the review article by Hornyak, Lauritsen, Morrison, and Fowler.[6]

II. PROCEDURE

The 180°-focusing magnetic pair spectrometer used in this work is similar to that of Walker and McDaniel[12] and has been described in a previous paper.[1] High energy gamma-rays were produced by bombarding thick targets of natural boron (about 18.8 percent B^{10}), enriched boron (96 percent B^{10}, obtained from the Oak Ridge National Laboratories), nitrogen, and fluorine with 1.56-Mev deuterons from the Rice Institute pressure Van de Graaff generator. The boron targets were in the form of B_2O_3, fused onto silver disks; the nitrogen and fluorine targets were the respective calcium compounds. (The calcium nitride was obtained from Metal Hydrides, Inc.) The calcium nitride target was scraped to a fresh surface immediately before it was placed in vacuum to remove the calcium hydroxide film which forms rapidly in the presence of water vapor. The deuterons were magnetically analyzed; the deuteron beam current, measured by a current integrator, was generally about 0.25 microampere. The geometry of the pair spectrometer and

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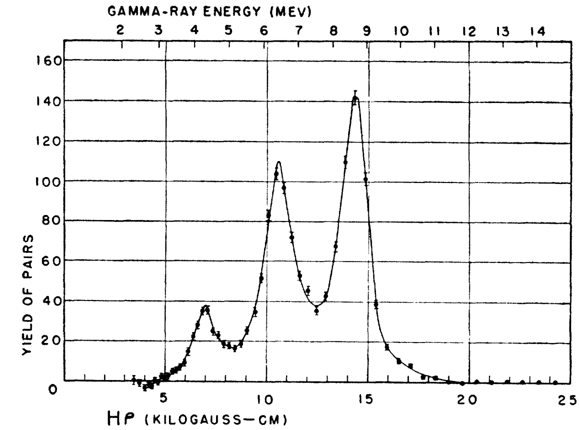

FIG. 1. Pair spectrum from deuteron bombardment of B_2O_3 (96 percent B^{10}). Ordinate scale is pair counts per 80 microcoulombs of deuterons.

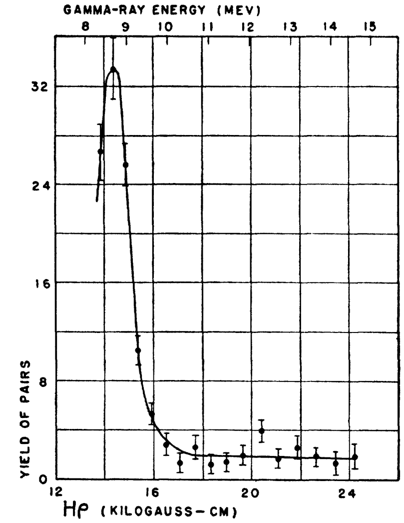

FIG. 3. Pair spectrum (high energy end) from deuteron bombardment of B_2O_3 (81 percent B^{11}). Ordinate scale is pair counts per 80 microcoulombs of deuterons.

the radiator thickness (31.0 mg/cm² tin) were the same as in the work with ThC″ and polonium-beryllium,[1] simplifying yield comparisons.

III. RESULTS

The results obtained are shown in Figs. 1 through 5, in which the yield of pairs is plotted as a function of $H\rho$ for either positron or electron in the case of equally shared energy. The ordinate units are the same for all figures and represent pair counts per 80 microcoulombs of deuterons for a single pair of counters. Small corrections have been made for nonradiator background and for accidental coincidences. Standard deviations are shown for each point, unless the deviation is covered by the area of the point. Each point on the graphs, except for a few on the ends, represents the weighted average of four determinations, one in each channel used; each determination was for 80 microcoulombs of deuterons, except for the main portions of the spectra from N^{14} and F^{19}, where each determination was for 160 microcoulombs. Each of these curves except Fig. 3 took about ten hours of running time, not including the shorter time needed to measure the nonradiator counting rate as a function of $H\rho$. The highest point in the $N^{14}+d$ curve represents about 2400 pair counts.

The gamma-ray spectra obtained with boron targets are shown in Figs. 1, 2, and 3. Figures 1 and 2 show the spectra from enriched and natural boron, respectively; Fig. 3 shows a more precise analysis of the high energy end of Fig. 2, indicating that the high energy fluctuations above the main peak are largely, if not entirely, statistical in nature. In each of these two spectra the same three lines appear; the two highest energy lines are five times stronger from B^{10} than from natural boron, indicating that they come from B^{10} only. The lowest energy line is of the same order of intensity in both spectra, so that it must come from both isotopes. Because of the overlapping of the lines, the width at half-maximum can be measured with some accuracy

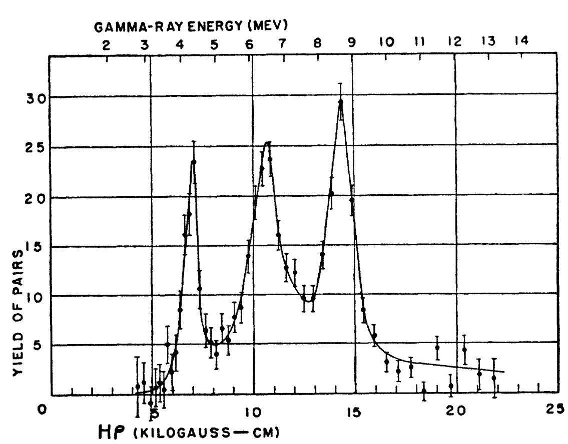

FIG. 2. Pair spectrum from deuteron bombardment of B_2O_3 (81 percent B^{11}). Ordinate scale is pair counts per 80 microcoulombs of deuterons.

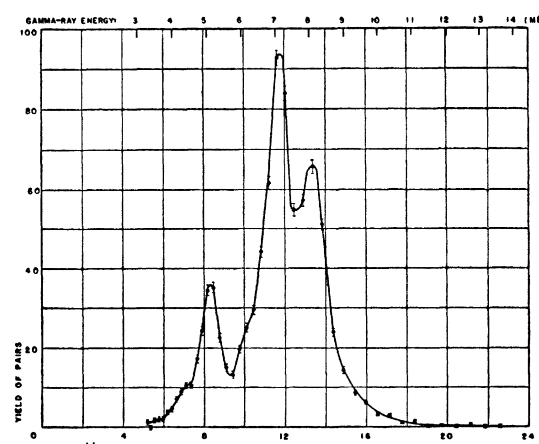

FIG. 4. Pair spectrum from deuteron bombardment of Ca_3N_2. Ordinate scale is pair counts per 80 microcoulombs of deuterons.

only for the line of highest energy from the enriched target, which has a width of 11.1 percent. The method of difference of squares used in the earlier work[1] then indicates a peak shift of 4.4 percent in momentum, if a single gamma-ray is responsible for the peak, which is doubtful (see below). Theoretical calculations of the effects of angular distribution of pairs leaving the radiator and of energy loss in the radiator lead to a peak shift of about 3 percent; a peak shift of 4.0 percent has been adopted as a compromise. No other peak width in any of the work reported here can be measured with equal accuracy. Therefore, the peak shift for other gamma-ray energies has been estimated by plotting a smooth curve through this value (4.0 percent at 9 Mev) and through the peak shifts used at lower energies[1] (4.9 percent at 4.45 Mev; 6.0 percent at 2.62 Mev).

Using these peak shifts to correct the energies, we find that the gamma-rays from $B^{10}+d$ have energies of 4.52, 6.71, and 9.04 Mev. The lines from natural boron have apparently identical energies, though the peaks cannot be located as accurately as for the separated isotope. The results are summarized in Table I.

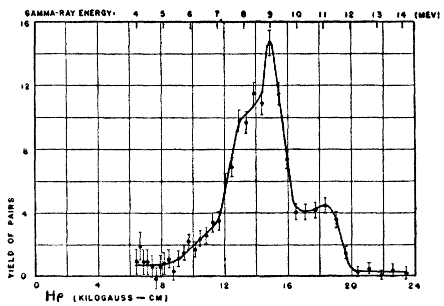

FIG. 5. Pair spectrum from deuteron bombardment of CaF_2. Ordinate scale is pair counts per 80 microcoulombs of deuterons.

The ratios of the yields from separated B^{10} to those from natural boron for the 6.7- and 9.0-Mev gamma-rays are respectively 4.6 and 5.2, which are equal to the ratio of 96 percent to 19 percent of B^{10} within statistical error. There is thus no doubt that these two gamma-rays are due to the B^{10} isotope. Any radiation from the heavier isotope in this range is very weak, if present, and is completely obscured by the strong high energy quanta from $B^{10}+d$. The calculated yield which would have been obtained from 100 percent separated boron isotopes is given in Table II. The 6.7-Mev gamma-ray peak appears to have too much width for a single gamma-ray, particularly on the high energy side. The results indicate that there is no appreciable gamma-radiation above 10 Mev from deuteron bombardment of B^{10}. In the region from 11.5- to 15-Mev statistical fluctuations are of the order of 0.5 percent of the peak counting rate. Allowing for the increased pair-production cross section in this energy range, we estimate the upper limit of possible gamma-radiation in this range as a few tenths of 1 percent of the intensity at 9 Mev. For the case of $B^{11}+d$ we estimate that there is no

TABLE I. Gamma-rays from $B+d$.

Target	$H\rho$ at peak (gauss-cm)	Gamma-ray energy (Mev)	Pair counts (per 80 microcoulombs)
B_2O_3	7000	4.52±0.10	38
(96% B^{10})	10,600	6.71±0.13	110
	14,400	9.04±0.18	141
B_2O_3	7000	4.5 ±0.1	23
(81% B^{11})	10,600	6.7 ±0.2	24
	14,400	9.0 ±0.2	27

gamma-radiation in this high energy range of the order of 1 or 2 percent of the intensity of the 4.5-Mev gamma-ray produced by this reaction.

In order to make sure that the 4.5-Mev gamma-ray actually came from both boron isotopes and not from another element, a check was made on the pair spectrum from a thick target of boron carbide. Because of considerable background, the spectrum was not observed with great accuracy, but it appeared to be identical with that from normal boron oxide, except that the yield was roughly 1.6 times as large. This difference is to be expected because of the larger percentage of boron atoms in boron carbide.

The pair spectrum produced by deuteron bombardment of the calcium nitride target is shown in Fig. 4. The high energy gamma-radiation is nearly as intense as that from $B^{10}+d$, with correspondingly good statistics. There are three well-defined peaks, corresponding to gamma-ray energies of 5.33, 7.40, and 8.46 Mev. There is some indication of unresolved lines at 4.4 and 6.4 Mev, of lower intensity.

The results obtained with a calcium fluoride target are plotted in Fig. 5. The pair yield is lower than in any of the other cases, with correspondingly larger statistical fluctuations. It is apparent that there are at least three high energy gamma-rays present, since the main peak is much too wide for a single gamma-ray. If we assume that there are three gamma-rays in this

TABLE II. Summary for gamma-rays produced by deuteron bombardment.

Target	$H\rho$ at peak (gauss-cm)	Gamma-ray energy (Mev)	Pair counts (per 80 micro-coulombs)	Gamma-ray yield (quanta/micro-coulomb)
B_2O_3	7000	4.52±0.10	39	34×10^6
(100% B^{10})	10,600	6.71±0.13	115	19×10^6
	14,400	9.04±0.18	147	12×10^6
B_2O_3 (100% B^{11})	7000	4.5 ±0.1	19	17×10^6
Ca_3N_2	(6800)	(4.4 ±0.3)	(4)	(4×10^6)
	8330	5.33±0.11	37	15×10^6
	(10,200)	(6.4 ±0.5)	(9)	(2×10^6)
	11,720	7.40±0.15	91	11×10^6
	13,450	8.46±0.17	57	5×10^6
CaF_2	12,800	8.1 ±0.4	5	0.5×10^6
	14,900	9.3 ±0.3	14	1.1×10^6
	18,500	11.5 ±0.4	3	0.2×10^6

spectrum, we obtain gamma-ray energies of 8.1, 9.3, and 11.5 Mev. It was not possible to obtain good statistics below 6 Mev, because of high nonradiator background in this range.

All of the experimental results reported in this paper are summarized in Table II. The pair counting rates have been converted roughly to absolute yield values by interpolating between spectrometer sensitivities found at lower energies and the theoretically calculated value at 9 Mev. It has been found[1] that, with this same geometry and radiator, this spectrometer counts one pair for each 8×10^9 quanta at 2.62 Mev, and one pair for each 7×10^7 quanta at 4.45 Mev. It becomes possible to calculate the sensitivity at higher energies with fair accuracy; the value obtained at 9.0 Mev is 6.5×10^6 quanta per pair count. This value takes into account only the geometry of the apparatus, the theoretical pair-production cross section, and an estimated 30 percent loss of counts due to angular distribution effects at this energy. Although the absolute yield values obtained in this way are not very accurate, they are probably not in error by much more than a factor of two.

Rough measurements of the intensity of gamma-radiation from deuteron bombardment of the boron targets, by comparison with radium gamma-radiation, using a small Geiger counter sheathed in $\frac{1}{2}$ inch of lead, indicated that the $B^{10}+d$ radiation was equivalent to 8 mg of radium per microampere of deuterons, and the normal boron target was equivalent to 5 mg per microampere. Making a rough estimate as to the counter efficiency at the various energies involved, we find that about 8×10^7 quanta/microcoulomb are obtained from the B^{10} target and about 6×10^7 from the normal isotopic mixture. These values are not inconsistent with the intensity values estimated in Table II, which indicates that the total high energy intensity is about 6.4×10^7 quanta/microcoulomb from the 96 percent B^{10} target, and about 2.6×10^7 from normal boron oxide. This includes only gamma-rays of more than 4-Mev energy, as the sensitivity of the spectrometer drops rapidly below this energy. To the extent that these intensity estimates are correct, most of the $B^{10}+d$ radiation is of energy greater than 4 Mev, while more than half of the weaker $B^{11}+d$ radiation is of lower energy. It is possible that an appreciable amount of low energy radiation comes from $O^{16}+d$ in each case.

IV. DISCUSSION

A. $B^{11}+d$

The high energy gamma-rays produced by bombardment of natural boron with deuterons have been observed in earlier cloud-chamber work. Gaerttner, Fowler, and Lauritsen,[2] bombarding with 550 to 850 kilovolts peak voltage, found gamma-rays of 1.5, 2.2 ± 0.3, 4.4 ± 0.3, 6.9 ± 0.4, and 9.1 ± 0.4 Mev, with relative intensities of >2.5, 2.5, 1.0, 0.3, and 0.1. Halpern and Crane[3] found lines of 1.4, 2.4, 4.2, 6.0, and 9.1 Mev, with relative intensities of 1, 1, 6, 2, and 1 (with 700-kev maximum deuteron energy). The present work does not give greatly different results for the natural boron target; the relative intensities of the 4.5-, 6.7-, and 9.0-Mev gamma-rays are approximately given (see Table II) by 10, 2, and 1. Because no work had been done with separated isotopes, the two highest energy lines were generally assigned[13] until very recently to the reaction $B^{11}(d,n)C^{12}$. As the present work and that of Rutherglen[5,6] show, these gamma-rays should have been assigned to $B^{10}+d$, only the 4.5-Mev quanta coming in part from $B^{11}+d$. Rutherglen has reported 4.5, 6.5, 6.7, and 8.94 Mev gamma-rays from $B^{10}+d$, and 4.45 Mev from $B^{11}+d$.

There are several reactions which might account for the 4.5-Mev gamma-ray observed from $B^{11}+d$. These are the following (Q-values taken from Hornyak, Lauritsen, Morrison, and Fowler[6]):

(1) $B^{11}(d,\alpha)Be^9$, $Q=8.03$ Mev.
(2) $B^{11}(d,p)B^{12}$, $Q=1.1$ Mev; $B^{12}(\beta^-)C^{12}$, $Q=13.4$ Mev.
(3) $B^{11}(d,n)C^{12}$, $Q=13.78$ Mev.

None of the high energy gamma-rays could come from $O^{16}+d$, because of insufficient Q-values. As to reaction (1), alpha-particle studies by Van Patter *et al.*[14] indicate a level in Be^9 at 2.42 Mev, but give no evidence of other levels up to 5.0-Mev excitation energy. Their estimated yield values at 1.51-Mev deuteron energy (1.6 millibarns/steradian for transitions to the 2.42-Mev level in Be^9, with transitions to other levels at least six times less intense) seem to rule out this reaction as the 4.5-Mev gamma-ray source, or even as the origin of much of the low energy radiation.

The second and third reactions lead to the same levels in C^{12}. At a deuteron bombarding energy of 1.47 Mev, Hudspeth and Swann[4] estimated the thick target yield from (2) to be about 10^7 beta-particles/microcoulomb. Hornyak and Lauritsen[15] found deviations in the beta-spectrum which suggest that about 5 percent of the beta-transitions are to excited levels of C^{12}. Thus, the high energy gamma-ray yield may be of the order or 5×10^5 quanta/microcoulomb, which seems entirely too small to account for the results reported in the present paper. The yield of 1-Mev gamma-rays from an excited level in B^{12} is reported as about 20 percent[16] of the yield of B^{12} (there is some conflicting data[4]), which might indicate 2×10^6 quanta/microcoulomb. If so, this reaction could not account for much of the low energy gamma-radiation from $B^{11}+d$.

Gibson[17] investigated reaction (3), using a separated B^{11} target 120 kev thick and deuterons of 930-kev

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energy, and found strong neutron groups of roughly equal intensity from 4.47- and 9.72-Mev levels in C^{12}, as well as a weak group corresponding to a 7-Mev level. Similar groups were found by Bonner and Brubaker[18] using unseparated isotopes and 0.9-Mev deuterons. The weak group in Gibson's work could be assigned to B^{10} contamination, as 5 percent contamination would account for its intensity. The main reason Gibson did not do this seems to be that the observed neutron energy was slightly too low; however, he observed a similar lowering of energy for neutrons from B^{11} contamination of the B^{10} target. There seems to be little strong evidence for a 7-Mev level in C^{12} in other recent work.[1,17,19–23]

The most reasonable explanation of the observed 4.5-Mev gamma-ray seems to be that it is from reaction (3), involving the well-verified[6] 4.5-Mev level in C^{12}. The absence of higher energy gamma-radiation is probably accounted for by the fact that the 9.7-Mev level in C^{12} is unstable to alpha-particle emission, the dissociation level being at 7.39 Mev. The lower energy gamma-radiation apparently present may come from a number of possible reactions, and may involve $O^{16}+d$.

B. $B^{10}+d$

Considering next the gamma-rays produced by $B^{10}+d$, we have the following possible reactions:

(1) $B^{10}(d,n)C^{11}$, $Q=6.53$ Mev;

$C^{11}(\beta^+)B^{11}$, $Q=0.98+1.02$ Mev.

(2) $B^{10}(d,\alpha)Be^8$, $Q=17.81$ Mev;

$Be^8\rightarrow 2He^4$, $Q=0.1$ Mev.

(3) $B^{10}(d,p)B^{11}$, $Q=9.24$ Mev.

Reaction (1) might account for the 4.5- and 6.7-Mev gamma-rays, as Swann and Hudspeth,[24] as well as Johnson,[25] have found evidence of levels in C^{11} at about these energies from studies of the neutron groups. Reaction (2) could account for all the gamma-rays on the basis of energy available. However, Thirion[26] has found no evidence for gamma-alpha-coincidences from $B^{10}+d$, at 600-kev deuteron energy. It is of interest to note that the 17.60-Mev state of Be^8 is evidently not excited by (2), since the known[12] 14- and 17-Mev gamma-rays from this state are not observed. The excitation of this level is improbable because of the low energy available for alpha-particle emission; but is not forbidden by selection rules, as C^{12} can apparently be formed in states of either parity[27] at the bombarding energy used here.

The most probable source of the gamma-rays seems to be reaction (3), the protons from which have been investigated by several observers. Bateson[28] observed levels in B^{11} at 2.15, 4.48, 5.03, 6.92, 7.82, 8.48, and 8.86 Mev, using separated B^{10} and 3.76-Mev deuterons. Van Patter and Buechner,[29,30] using 96 percent B^{10} and 1.5 Mev deuterons, have found levels, in B^{11} at 2.138, 4.459, 5.034, 6.758, 6.808, 7.298, 8.568, 8.926, 9.190, and 9.276 Mev. The weakest proton groups were those corresponding to the 2.138-, 6.808-, and 8.568-Mev levels.[30] This level structure fits the observed gamma-ray spectrum quite well; thus, the asymmetry of the 6.7-Mev gamma-ray peak may be due to the presence of a 7.3-Mev gamma-ray. Obviously, gamma-rays of 8.926, 9.190, and 9.276 Mev would not be resolved by this spectrometer. Curling and Newton[31] have observed proton-gamma-coincidences from (3). At their bombarding energy of 430 kev the lower energy proton group, to the 4.5-Mev level in B^{11}, was 3.5 times as intense as the group to the 2.1-Mev level, whether or not coincidence with gamma-rays was required. This evidence is consistent with the small amount of low energy radiation produced by $B^{10}+d$, as observed in the present work.

C. $N^{14}+d$

The gamma-ray spectrum from $N^{14}+d$ has been reported in earlier cloud-chamber work. Gaerttner and Pardue,[7] bombarding at 700 kev, found gamma-rays of energy 2.2, 4.2, 5.3±0.4, 7.2±0.4, and up to 11 Mev; Crane, Halpern, and Oleson[8] measured the energies as 2.5, 4.1, 5.1±0.3, 6.6±0.3, and 8.2±0.5 (deuteron energy 0.6 Mev). The values found with this pair spectrometer are (4.4±0.3), 5.33±0.11, (6.4±0.5), 7.40±0.15, and 8.46±0.17, which agree reasonably well with the earlier results. Reactions which must be considered include the following:

(1) $N^{14}(d,\alpha)C^{12}$, $Q=13.50$ Mev.

(2) $N^{14}(d,n)O^{15}$, $Q=5.1$ Mev;

$O^{15}(\beta^+)N^{15}$, $Q=1.68+1.02$ Mev.

(3) $N^{14}(d,p)N^{15}$, $Q=8.57$ Mev.

Reaction (1) has been observed in various laboratories. Holloway and Moore,[32] bombarding enriched mixtures of nitrogen isotopes with 1-Mev deuterons, observed alpha-groups from N^{14} leading to C^{12} levels at 4.37 and 7.62 Mev, the latter group being weak. Guggenheimer, Heitler, and Powell,[23] bombarding gase-

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[31] C. D. Curling and J. O. Newton, Nature **166**, 339 (1950).
[32] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).

ous nitrogen with 6.5-Mev deuterons, observed these same groups with less statistical accuracy. However, Malm and Buechner,[20] using 1.4-Mev deuterons, performed a magnetic analysis of the alpha-particles from (1) and found evidence of excited C^{12} levels only at 4.438 and 9.620 Mev, with no group from a 7-Mev level to about 10 percent of the intensity. They also observed that the 9.620-Mev level was unusually wide, presumably due to dissociation into Be^8+He^4. Thus, it seems certain only that a 4.5-Mev gamma-ray should be produced by this reaction.

Reaction (2) does not produce enough energy to account for the highest energy gamma-rays. There is evidence that two neutron groups are present,[33,34] the less energetic group involving a 4.0-Mev level in O^{15}, which could account for some of the 4.4-Mev gamma-radiation.

Reaction (3) is the probable source of all of the gamma-rays of energy higher than 4.4 Mev. The recent work of Malm and Buechner[35] on magnetic analysis of the proton groups (1.42-Mev bombarding energy) gives evidence of levels in N^{15} at 5.276, 5.305, 6.328, 7.164, 7.309, and 8.315 Mev. Wyly[36] has found, by absorption methods, levels at 5.32, 6.31, and 7.21 Mev, and some evidence of an 8.2-Mev level (deuteron energy 3.32 Mev). Kinsey, Bartholomew, and Walker[37] found levels in N^{15}, from the reaction $N^{14}(n,\gamma)N^{15}$, at 5.29, 6.32, 7.16, 7.36, 8.28, and 9.16 Mev. All of these energy level values are consistent with the gamma-ray energies greater than 4.4 Mev from $N^{14}+d$.

D. $F^{19}+d$

The gamma-rays observed with this spectrometer from $F^{19}+d$ have not previously been reported. Earlier work by Bennett, Bonner, and Watt,[9] using absorption methods, indicated a complex gamma-ray spectrum with a maximum of 6.7 Mev. The following reactions can take place for $F^{19}+d$:

(1) $F^{19}(d,\alpha)O^{17}$, $Q=10.07$ Mev.

(2) $F^{19}(d,p)F^{20}$, $Q=4.3$ Mev; $F^{20}(\beta^-)Ne^{20}$, $Q=7.2$ Mev.

(3) $F^{19}(d,n)Ne^{20}$, $Q=10.72$ Mev.

Energy levels in O^{17} have been found at 7.60 and 8.23 Mev by Rotblat,[5,6] from a study of the alpha-particle groups of (1), at 7.8-Mev bombarding energy. Thus, the 8.1-Mev gamma-ray may be produced by (1); as to the 9.3- and 11.5-Mev gamma-rays, penetrability considerations make (1) improbable and impossible, respectively, as the source. It is, of course, possible that there are more than three high energy gamma-rays from $F^{19}+d$, as they are not fully resolved in the present work. We can rule out reaction (2) in any case, as not releasing enough energy.

Reaction (3) is certainly responsible for the 11.5-Mev gamma-ray, indicating a level in Ne^{20} at 11.5 ± 0.4 Mev, and may be responsible for all the high energy quanta. Neutron groups from (3) have been observed by Bonner[38] and by Powell[39] at energies corresponding to levels of Ne^{20} at 7.8, 9.0, and 10.1 Mev, as well as at lower energies. The uppermost of these levels can decay into $O^{16}+He^4$, as observed by French, Meyer, and Treacy,[40] who found 9.7 Mev as the energy of the level. The levels at 7.8 and 9.0 Mev may be responsible for the 8.1 ± 0.4- and 9.3 ± 0.3-Mev gamma-rays.

There seems to be no previous direct evidence for a level in Ne^{20} at 11.5 ± 0.4 Mev, but this level may be involved in the high energy capture radiation produced at the 669-kev resonance for $F^{19}(p,\gamma)Ne^{20}$. Rae, Rutherglen, and Smyth,[41] using a pair spectrometer, have recently observed 12.0 ± 0.2-Mev gamma-radiation at this resonance; Carver and Wilkinson[42] have found the energy to be 12.09 ± 0.28 Mev, by measuring the energy of photoprotons from deuterium. This capture radiation has been interpreted as a transition between the 13.4-Mev resonance level in Ne^{20} and a known 1.4-Mev level,[6,10,11] but may be due to a cascade transition between the levels of Ne^{20} at 13.4 Mev, 11.5 ± 0.4 Mev, and the ground state.

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