Gamma Radiation from Deuterons on Several Light Nuclei*

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A single crystal NaI scintillation spectrometer has been used to measure the energy of gamma rays from $B^{10}+d$, $B^{11}+d$, $N^{14}+d$, $C^{12}+d$, $F^{19}+d$, and $Si^{28}+d$. Several gamma rays were found and their energy and relative intensity are given. It is also deduced what transitions these gamma rays represent.

INTRODUCTION

ONE of the ways to study the energy levels of nuclei is to measure the energy and relative intensity of the gamma rays produced under charged particle bombardment. This has not been done completely for low-energy gamma rays from deuteron bombardment of several light elements. Pair spectrometers have been used to study the high-energy gamma rays from most deuteron reactions among the light elements.[1–4] The low-energy gamma rays have been studied in the case of Li^7+d, Be^9+d, $C^{12}+d$, and $C^{13}+d$.[5] This investigation concerns low-energy gamma rays from $B^{10}+d$, $B^{11}+d$, $N^{14}+d$, $F^{19}+d$, $C^{12}+d$, and $Si^{28}+d$.

APPARATUS AND EXPERIMENTAL PROCEDURE

A NaI scintillation spectrometer was used to measure the energy of the gamma rays produced. A NaI crystal $1\frac{1}{2}$ inches in diameter by 1 inch in length, commercially prepared by The Harshaw Chemical Company, was mounted on a Du Mont 6292 photomultiplier tube in the standard manner. The pulses from the photomultiplier tube went through a standard cathode follower preamplifier, an A-1 linear amplifier, a single channel pulse-height analyzer, and scaler. The photoelectric peak of the 661-kev gamma ray from Cs^{137} had a full width at half-maximum of not more than 10 percent and a peak to valley ratio not less than 18 to 1.

The deuterons were accelerated by the 2-Mev Rice Institute Van de Graaff accelerator. The magnetic analyzer and regulator were used to hold the beam at constant energy. The NaI crystal was placed directly behind the target that was to be bombarded by deuterons. The axis of the NaI photomultiplier tube combination coincided with the extension of the line of flight of the deuteron beam. The distance of the front face of the crystal from the target varied from 1 inch to 10 inches depending on the intensity of the gamma rays from the reaction.

Differential pulse-height curves were run from 10 volts to 60 or more volts. The window of the pulse-height analyzer was set at 1.00 volt, and points were taken every volt. The number of gamma rays from the target were monitored by the current integrator. Statistics on the points shown are between 2 and 3 percent.

The energy of an unknown gamma ray was measured by first changing the gain of the amplifier until the peak to be measured was between 40 and 50 volts. Several alternating runs were made over the peak to be measured and over a calibration peak chosen to be as close as possible to the unknown peak. A rotating target holder was used, and the beam was allowed to bombard a silver blank while running on the calibration peak.

Background was almost negligible above a γ-ray energy of 600 kev. Below 600 kev, however, difficulties were experienced because of low-energy gamma radiation produced in the NaI crystal by neutrons and also because of the annihilation radiation from some of the reaction products.

$B^{10}+d$

The B^{10} target was made of 96 percent B^{10} and 4 percent B^{11}. Targets were made both by evaporating elemental boron off a tungsten filament upon a silver blank in a vacuum and by pressing elemental boron upon a silver blank.

No gamma rays from $B^{10}+d$ could be resolved below the well-known 4.46-Mev gamma ray from $B^{10}(d,p)B^{11}$.[1–4] There seemed to be several unresolved peaks between 1.5 and 2.5 Mev. Many attempts were made to resolve these gamma rays but without success. Annihilation radiation and neutron background made it difficult to see weak low-energy lines. However, no strong low-energy lines were present.

$B^{11}+d$

The B^{11} target was composed of 81 percent B^{11} and 19 percent B^{10}. It was made by evaporating natural boron off a tungsten filament upon a silver blank.

The pulse-height distribution of B^{11} bombarded by 1.05-Mev deuterons is shown in Fig. 1. The upper curve was taken at a higher amplifier gain than the lower curve. The peaks marked 940 kev and 1.64 Mev are the photoelectric peaks of gamma rays of these

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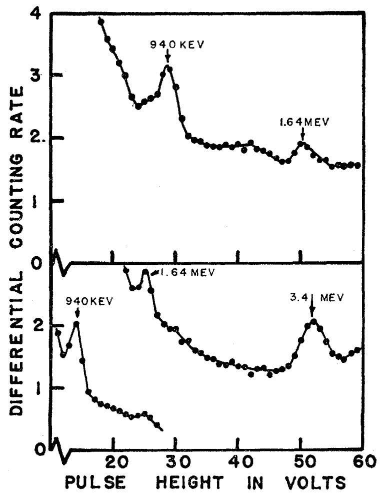

FIG. 1. Pulse-height distribution obtained from $B^{11}+d$.

energies. They probably represent the decay to the ground state of the 0.947- and 1.65-Mev levels[6] in B^{12} made by the $B^{11}(d,p)B^{12}$ reactions. The peak marked 3.41 Mev is the pair peak with the escape of both annihilation photons of the well-known 4.43-Mev gamma ray from the $B^{11}(d,n)C^{12}$ reaction.[1-3] The relative intensities of the 940-kev, 1.64-Mev, and 4.43-Mev gamma rays are approximately 2, 1, and 2.

$N^{14}+d$

The N^{14} target was made by pressing CrN upon a silver blank. The pulse height distribution of this target bombarded by 1.05-Mev deuterons is shown in Fig. 2. The upper curve was taken at a higher amplifier gain than the lower curve.

The peak marked 1.88 Mev is the photoelectric peak of a 1.88-Mev gamma ray. It probably represents a cascade decay of the 7.16-Mev level in N^{15} (made by the $N^{14}(d,p)N^{15}$ reaction) to the 5.28- or 5.31-Mev levels[7] in N^{15}. This may be deduced for the following reasons: (1) the 1.88-Mev gamma ray is almost exactly the correct energy for this transition, (2) work with a pair spectrometer on the $N^{14}+d$ reaction indicates that all levels in N^{15} below 10-Mev decay directly to the ground state except the 7.16-Mev level,[4] (3) the ratio of the intensity of the 1.88-Mev gamma ray to the intensity of the 5.3-Mev gamma ray is equal within the large experimental errors to the ratio of the proton yield from the 7.16-Mev level to the total proton yield from the 5.28-, 5.31-, and 7.16-Mev levels reported elsewhere.[8]

From a study of the angular distribution of protons from the $N^{14}(d,p)N^{15}$ reaction, Gibson and Thomas report that either the 7.32- or 7.16-Mev levels in N^{15} or both have a spin of $\frac{1}{2}+$ or $\frac{3}{2}+$ and that the 5.31- and 5.28-Mev levels have a large spin.[9] It may be concluded, therefore, that the 7.32-Mev level has the spin $\frac{1}{2}+$ on $\frac{3}{2}+$ since it does decay directly to the ground state[4] and that the 7.16-Mev level has spin $\frac{5}{2}$ or more.

The peak marked 0.84 Mev may be a combination of three effects. (1) The pair peak with the escape of both annihilation photons of the 1.88-Mev gamma ray would be expected to give a small peak. However, this peak is probably too large to be attributed to this effect alone. (2) It may be that the 7.16-Mev level does decay to the 6.33-Mev level as well as the doublet at 5.3 Mev. This is still in keeping with our earlier conclusion since Gibson and Thomas conclude that the 6.33-Mev level may have a spin as large as $\frac{5}{2}-$. If this cascade to the 6.33-Mev level does occur, the cascade to the 5.3-Mev doublet occurs at least 20 times as often. (3) There is always some oxygen impurity in the target and the 875-kev gamma ray from $O^{16}(d,p)O^{17}$ would be expected.

The peak marked 3.40 Mev is probably the pair peak with the escape of both annihilation photons of the 4.43-Mev gamma ray from the $N^{14}(d,\alpha)C^{12}$ reaction. The relative intensities of the 1.88-Mev, 4.43-Mev, and 5.3-Mev gamma rays are approximately as 2.5, 1, and 7.

$C^{12}+d$

A C^{12} target was made by cracking methyl iodide on a heated tungsten filament. Besides the well-known 3.08-Mev gamma ray from $C^{12}(d,p)C^{13}$, a higher energy component of 3.68 Mev has been reported at 3-Mev deuteron bombarding energy.[10] This gamma ray

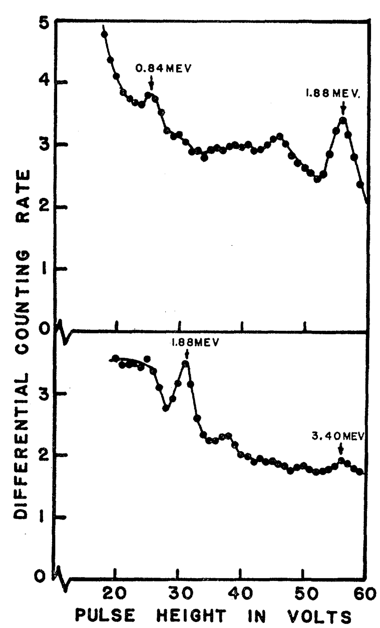

FIG. 2. Pulse-height distribution obtained from $N^{14}+d$.

[6] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952); see p. 354.
[7] See reference 6, p. 371.
[8] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).
[9] W. M. Gibson and E. E. Thomas, Proc. Roy. Soc. (London) **210**, 543 (1952).
[10] See reference 6, p. 363.

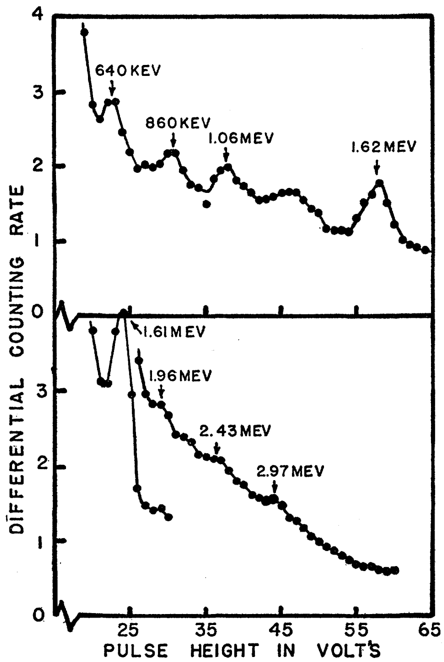

FIG. 3. Pulse-height distribution obtained from $F^{19}+d$.

presumably comes from the decay of the 3.68-Mev level in C^{13} to the ground state. It was thought interesting to see if this higher energy component could be detected at deuteron bombarding energies below 2 Mev.

At 1.35-Mev deuteron bombarding energy this higher energy component could not be detected. At 1.60 Mev a component of about 3.7-Mev energy was detected with an intensity about 1/20 that of the well-known 3.08-Mev gamma ray.

$F^{19}+d$

The F^{19} target was made by evaporating CaF off a tungsten filament upon a silver blank. The pulse-height distribution obtained from $F^{19}+d$ at a deuteron bombarding energy of 1.05 Mev is shown in the upper half of Fig. 3. The peak marked 1.62 Mev corresponds to the photoelectric peak of a gamma ray of 1.62-Mev energy. It results from the decay to the ground state of the 1.63-Mev level[11] in Ne^{20}. This level may be excited directly in the $F^{19}(d,n)Ne^{20}$ reaction, but most of its intensity comes from the beta decay of F^{20} [12] made in the $F^{19}(d,p)F^{20}$ reaction to the 1.63-Mev level in Ne^{20}. From intensity studies with beam "on" and "off", it was concluded that the peak was due almost entirely to the $F^{19}(d,p)F^{20}$ reaction.

The peaks marked 640 kev and 1.06 Mev may be attributed to the decay to the ground state of the 0.65- and 1.06-Mev levels[12] of F^{20}. This result seems logical since the proton groups to these levels are more intense than to any other low-lying levels in F^{20}.[13]

The gamma ray marked 860 kev may be due to the decay to the ground state of O^{17} made in the $F^{19}(d,\alpha)O^{17}$ reaction. On the other hand, this same gamma ray may arise from an oxygen impurity in the target and come from $O^{16}(d,p)O^{17}$. Below 640 kev the only intense lines were the 0.11- and 0.19-Mev gamma rays of F^{19} from inelastic scattering. The relative intensities of the 640-kev, 1.06-Mev, and 1.62-Mev gamma rays are 1, 2.5, and 9.

The lower curve in Fig. 3 was made on the 6-Mev Van de Graaff at a bombarding energy of 3.97 Mev. The results suggest a gamma ray of 2.97-Mev energy upon almost a continuum of gamma-ray energies. So many gamma rays are possible from $F^{19}+d$ that it is almost impossible to determine with any certainly what transition the 2.97-Mev gamma ray represents.

QUARTZ+d

A block of quartz $\frac{3}{4}$ in.$\times\frac{3}{4}$ in.$\times\frac{1}{8}$ in. was used as a target. Quartz is almost pure SiO_2. Silicon is 92 percent Si^{28}. Therefore, the target was largely one atom of Si^{28} to two atoms of O^{16}.

This target was bombarded with 1.35-Mev deuterons. At this bombarding energy, no gamma rays from O^{16} except the 875-kev gamma ray from $O^{16}(d,p)O^{17}$ are expected. The most intense higher energy gamma rays would be expected from $Si^{28}+d$.

The pulse-height distribution above 1-Mev gamma-ray energy from quartz$+d$ at 1.35-Mev bombarding energy is shown in Fig. 4. The three peaks in the lower curve marked 3.91, 4.39, and 4.86 Mev all are pair peaks of the same gamma ray and probably represent the decay to the ground state of any or all of the

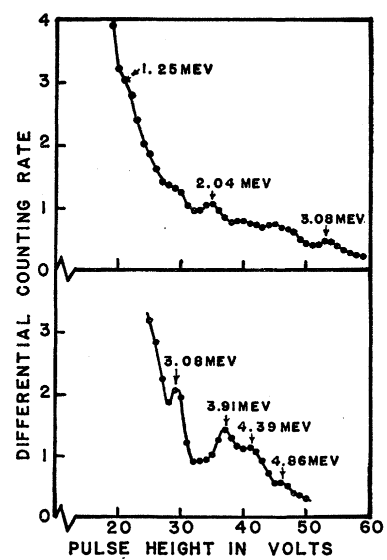

FIG. 4. Pulse-height distribution obtained from quartz$+d$.

[11] See reference 6, p. 390.
[12] See reference 6, p. 388.
[13] H. A. Watson and W. W. Buechner, Phys. Rev. 88, 1324 (1952).

4.84-, 4.90-, and 4.93-Mev levels[14] in Si^{29}. Below 1.2 Mev the curve rises because the 875-kev gamma ray from O^{16} is much stronger than any of the gamma rays from Si^{28}. When the region in the neighborhood of the change of slope marked 1.25 Mev in the upper curve was investigated under more favorable conditions of counting rate and window width, a peak was found at a gamma-ray energy of 1.25 Mev. This probably comes from the $Si^{28}(d,p)Si^{29}$ reaction and represents the decay to the ground state of the 1.28-Mev level[14] in Si^{29}.

[14] Endt, Van Patten, Buechner, and Sperduto, Phys. Rev. 83, 491 (1951).

In the energy region between 1.25 and 3.91 Mev, other gamma rays are indicated, but it is difficult to be conclusive for at least two reasons: (1) a little carbon contamination would give a big effect in comparison to the effect from Si^{28}, and the 3.08-Mev gamma ray from $C^{12}(d,p)C^{13}$ has peaks at 2.06, 2.57, and 3.08 Mev; (2) Si^{29} has five excited states in this region by $Si^{28}(d,p)Si^{29}$,[14] and it would be difficult to resolve them since one gamma ray may have as many as three peaks.

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Nuclear Forces and β Decay Matrix Elements

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The matrix elements of β decay are reduced to nonrelativistic form under the assumption that the nuclear Hamiltonian contains interactions involving odd operators. Particular attention is given to an interaction which gives rise to a spin orbit effect.

THE effect of nuclear forces on the β-decay matrix elements which involve odd operators has been discussed by a number of authors.[1–7] The matrix element of prime interest in these papers has been the pseudoscalar matrix element.

Peaslee[3] and Rose and Osborn[6] have shown that if the nuclear forces are due to two-body interactions and if these interactions are limited to even-even or odd-odd operators, then the nuclear forces have little effect upon the nonrelativistic form of the matrix elements.

Since there exists no satisfactory treatment of the relativistic two-nucleon problem, this note is limited to a consideration of the Hamiltonian of a nucleon interacting with various types of fields. The Foldy-Wouthysen transformation[8,9] has been employed to reduce the problem to a Schroedinger-Pauli form. This method is essentially the same as that used by Rose and Osborn.[6]

The nuclear Hamiltonian may be written as

$$H=-\beta M-\boldsymbol{\alpha}\cdot\mathbf{p}+\mathcal{E}+\mathcal{O};\tag{1}$$

$\mathcal{E}$ indicates interactions containing only even operators and $\mathcal{O}$, odd operators.[10] Interactions involving only even operators affect the nonrelativistic form to the matrix elements by adding only terms of order $1/M^2$, and these should be negligible.[6] However, Konopinski[7] has suggested that if the nuclear "Thomas" term,[11] a second-order term, is for some reason large enough to account for the nuclear inverted doublets, then one would also expect the effect, also second order, on the pseudoscalar matrix element of the scalar nuclear potential to be enhanced. Rather than consider such anomalous effects, we will consider only contributions of terms in $\mathcal{O}$ which are of first order in $1/M$.

In general $\mathcal{O}$ has the form

$$\mathcal{O}=\boldsymbol{\alpha}\cdot\mathbf{V}+i\beta\boldsymbol{\alpha}\cdot\mathbf{F}+\gamma_5\theta+i\beta\gamma_5\varphi.\tag{2}$$

The $\mathbf{V}$, $\mathbf{F}$, θ, and φ are field quantities with the proper transformation properties.

In the low energy limit, the β decay matrix elements become[2]

$$\int\boldsymbol{\alpha}\approx-(1/M)\int[\mathbf{p}-\mathbf{V}-\boldsymbol{\sigma}\times\mathbf{F}-\theta\boldsymbol{\sigma}],\tag{3a}$$

$$i\int\beta\boldsymbol{\alpha}\approx(1/M)\int[\boldsymbol{\sigma}\times\mathbf{p}+\boldsymbol{\sigma}\times\mathbf{V}-\mathbf{F}-\varphi\boldsymbol{\sigma}],\tag{3b}$$

$$\int\gamma_5\approx(1/M)\int[\boldsymbol{\sigma}\cdot\mathbf{p}-\boldsymbol{\sigma}\cdot\mathbf{V}-\theta],\tag{3c}$$

[1] M. Ruderman, Phys. Rev. 89, 1227 (1953).
[2] R. Herbst and A. Bushkovitch, Phys. Rev. 91, 442 (1953); also thesis, St. Louis University, 1953 (unpublished).
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[4] H. Takebe, Progr. Theoret. Phys. (Japan) 10, 673 (1953).
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[6] M. E. Rose and H. K. Osborn, Phys. Rev. 93, 1315 (1954).
[7] E. J. Konopinski, Phys. Rev. 94, 492 (1954).
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[9] W. Barker and Z. Chraplyvy, Phys. Rev. 89, 446 (1953).
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