Gamma Rays from the Reactions $Be^9(\alpha,n\gamma)C^{12}$, $C^{13}(d,p\gamma)C^{14}$, $N^{14}(d,p\gamma)N^{15}$, and $N^{14}(d,n\gamma)O^{15}$†

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(Received June 15, 1955)

A magnetic-lens pair spectrometer has been used to study the radiations produced by the bombardment of certain light nuclei with α particles and deuterons from The Rice Institute Van de Graaff accelerator. From the bombardment of Be^9 with 4.3-Mev α particles a single γ ray was observed at 4.48±0.06 Mev, doppler corrected. No 7.6-Mev nuclear pair line was observed with an intensity as great as 5% that of the 4.48-Mev internal pair line. No 3.2-Mev γ radiation was observed with an intensity as great as 8% that of the 4.48-Mev γ ray. A comparison of the internal and external pair spectra from the $C^{13}(d,p\gamma)C^{14}$ reaction has been made to obtain information on the multipolarities of the 6.1- and 6.7-Mev γ rays from C^{14}. If the 6.1-Mev γ ray is assumed to be $E1$, the relative intensities of the 6.1- and 6.7-Mev lines suggest that the 6.7-Mev γ ray is $E2$; however, other multipoles such as $E1$, $M1$, and $E3$ cannot be excluded. A study of the γ rays from the reactions $N^{14}(d,p\gamma)N^{15}$ and $N^{14}(d,n\gamma)O^{15}$ shows that the (d,p) cross section is 2.6 times larger than the (d,n) cross section at 2.4-Mev bombarding energy, whereas the two cross sections are about equal at 5.3-Mev bombarding energy.

I. INTRODUCTION

THE magnetic lens pair spectrometer used to make the measurements reported in this paper has been described in an earlier paper.[1] Surveys at 2.5 percent resolution of the γ rays from the deuteron bombardment of C^{13} and N^{14} have been reported earlier.[1,2] More detailed studies of certain aspects of these two reactions are reported here. The recent installation of an α-particle source on The Rice Institute 6-Mev Van de Graaff accelerator has made possible a study of the radiations from the $Be^9(\alpha,n\gamma)C^{12}$ reaction.

II. $Be^9(\alpha,n\gamma)C^{12}$

The absence of ground-state γ-ray transitions from the 7.6-Mev state of C^{12} suggests that the angular momentum of this state is zero. The decay of this state to the 0^+ ground state by the emission of nuclear pairs has been reported by Harries.[3] Several attempts have been made with the pair spectrometer in this laboratory to observe 7.6-Mev nuclear pairs from the reactions $B^{11}(p,\gamma)^*C^{12}$, $B^{11}(d,n)^*C^{12}$, and $N^{14}(d,\alpha)^*C^{12}$. These experiments all yielded negative results.[1,2] The $Be^9(\alpha,n)^*$-C^{12} reaction is particularly well suited for this purpose since the background due to competing reactions is low.

In order to have high intensity, the intermediate image spectrometer arrangement giving 5.5% resolution was used. The internal pair spectrum obtained from the bombardment of a 25 mg/cm² metallic beryllium target with 4.3-Mev α particles is shown in Fig. 1, uncorrected for background effects. The spectrum shows a single peak at 4.51±0.05 Mev, uncorrected for a doppler shift. No line was observed at 7.6 Mev with an intensity as great as 5% that of the 4.4-Mev line. A search was also made for a 3.2-Mev internal pair line which would result from the decay of the 7.6-Mev state to the 4.43-Mev state; however, no 3.2-Mev line was observed with an intensity as great as 5 percent of that of the 4.4-Mev line. The results are summarized in Table I.

A third possible mode of decay for the 7.6-Mev state of C^{12} is into $Be^8+\alpha$. The probability for this can be estimated in the following way. The single particle model suggests that the lifetime for the 3.2 Mev $E2$ transition should be about 7×10^{-13} sec.[4] If the lifetime for the emission of nuclear pairs is assumed to be about equal to that for the similar transition in O^{16}, (5×10^{-11} sec),[5] it follows that the γ-ray cascade transition from the 7.6-Mev state to the 4.4-Mev state is about 70

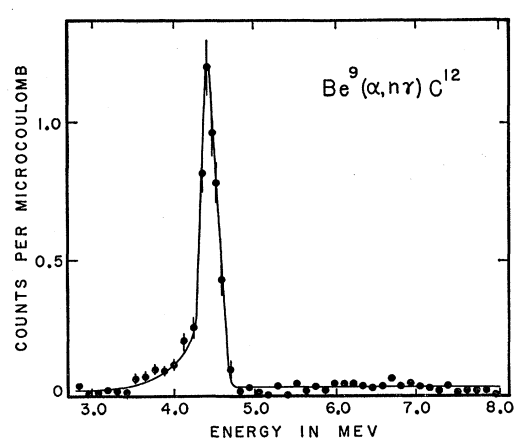

FIG. 1. Internal pair spectrum from the bombardment of a 25 mg/cm² metallic beryllium target with 4.3-Mev α-particles. Spectrometer resolution = 5.5%.

† Supported in part by the U. S. Atomic Energy Commission.
* Now at Columbia University, New York, New York.
[1] Bent, Bonner, and Sippel, Phys. Rev. **98**, 1237 (1955).
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[3] G. Harries and W. T. Davies, Proc. Phys. Soc. (London) **A65**, 564 (1952); G. Harries, Proc. Phys. Soc. (London) **A67**, 153 (1954).
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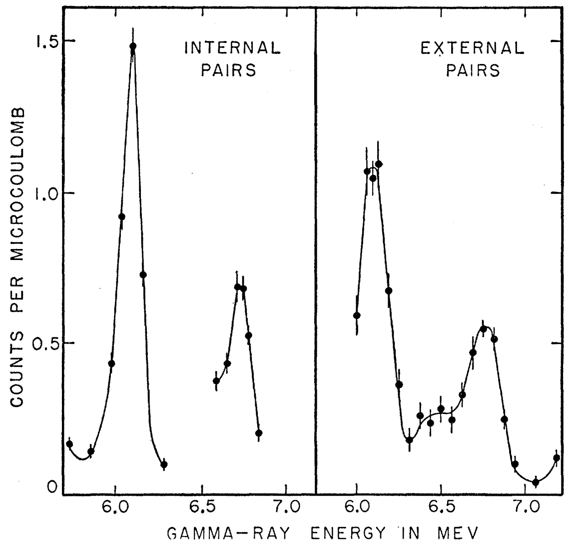

FIG. 2. Internal and external pair spectra of the 6.1- and 6.7-Mev γ rays from the reaction $C^{13}(d,p\gamma)C^{14}$. For the external pair measurement the 3 mg/cm² 48% C^{13} target was separated from a thorium converter 2 mils thick by 2 mm of aluminum. $E_d=4.1$ Mev. Spectrometer resolution=2.5%.

times more probable than the emission of 7.6-Mev nuclear pairs. The pair spectrometer, however, is about 1000 times more efficient for detecting nuclear pairs than for detecting 3.2-Mev γ rays, since the internal pair formation coefficient for a 3.2-Mev γ ray is about 1.3×10^{-3}.[6] According to the data of Guier, Bertini, and Roberts,[7] the ratio of the intensities of the neutron groups to the 4.4- and 7.6-Mev states is about 8:1. Therefore, if the 7.6-Mev state does not break up into $Be^8+\alpha$ at all, the intensity of the 7.6-Mev nuclear pair line should be 1.3 times greater than that of the 4.4-Mev line. The failure to observe a 7.6-Mev nuclear pair line with an intensity as great as 5% that of the 4.4-Mev internal pair line indicates that the 7.6-Mev state breaks up into $Be^8+\alpha$ with a probability greater than 96%. This interpretation is in agreement with that of Miller, Rasmussen, and Sampson[8] who, with 22-Mev α particles, failed to observe recoil C^{12} nuclei corresponding to the inelastic α-particle group leaving C^{12} excited in the 7.6-Mev state. They estimated that the probability for decay of the 7.6-Mev state into $Be^8+\alpha$ is greater than 80 percent.

TABLE I. Energy and yield of the γ ray from the $Be^9(\alpha,n\gamma)C^{12}$ reaction.

Uncorrected energy (Mev)	Doppler corrected energy (Mev)	Yield ($\gamma/\alpha\times10^6$)	Total cross section[a] (mb)
4.51±0.05	4.48±0.06	0.8	3

[a] Average value $E_\alpha=0$ to 4.3 Mev.

III. $C^{13}(d,p\gamma)C^{14}$

The efficiency of the pair spectrometer for detecting internal pairs is a function of the energy and multipolarity of the transitions, whereas the efficiency for detecting external pairs is a function of the energy only (for a given radiator). It should be possible, therefore, to obtain information on the multipolarities of γ ray transitions by comparing the yields of internal and external pairs.

In order to test this technique, and also to obtain information on the spins and parities of the first two excited states of C^{14}, both the internal and external pair peaks of the 6.1- and 6.7-Mev γ rays from the $C^{13}(d,p\gamma)C^{14}$ reaction were observed. The results obtained at 4.1-Mev bombarding energy are shown in Fig. 2. A 3 mg/cm² 48% C^{13} target was used for both measurements. For the external measurement the target was separated from a 2-mil thorium converter by 2 mm of aluminum absorber. The aluminum absorber was necessary in order to prevent the internal pairs formed in the target from contributing to the external pair spectrum formed in the converter. Enough silver was placed behind the target to prevent the beam from striking the aluminum absorber.

The number of internal pairs transmitted by the spectrometer per quantum has been calculated[2] as a function of the γ-ray energy and multipolarity for the spectrometer arrangement used in the present experiment. The dependence of the cross section for the production of external pairs on γ-ray energy is given by Heitler.[9] The ratio of the intensities of the two external pair peaks, when corrected for the energy dependence of the external pair cross section, gives the ratio of the intensities of the 6.1- and 6.7-Mev γ rays (assuming that the angular distributions of the two γ rays with respect to the beam are not appreciably different). If the multipolarities of the 6.1- and 6.7-Mev γ rays are the same, then the ratio of the intensities of the internal pair peaks, corrected for the energy dependence of the internal pair formation coefficients, should be the same as the ratio obtained from the external pair measurement. A difference in the ratios can be explained by assuming that the multipolarities of the two transitions are different. If the multipolarity of one of the γ rays is known, then information as to the multipolarity of the other can be obtained in this manner. Measurements of the angular distributions of the proton groups from the $C^{13}(d,p)^*C^{14}$ reaction[10] together with measurements of the energy distribution of the internally formed positrons[11] indicate that the spin and parity of the 6.1-Mev state of C^{14} are 1^-. In the present experiment the intensities of the γ rays

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were obtained from the heights of the peaks. For the external pairs the ratio of the 6.7-Mev peak height to the 6.1-Mev peak height is 0.51 ± 0.04, whereas for the internal pairs this ratio is 0.47 ± 0.03. If the 6.1-Mev transition is assumed to be $E1$, the ratios can best be explained by assuming that the 6.7-Mev transition is $E2$; however, $E1$, $M1$, and $E3$ are also possible assignments within the experimental errors. $M2$ and $E4$ are slightly outside of the experimental errors, and higher multipole orders seem unlikely. Table II gives possible assignments for the 6.7-Mev transition which are consistent with other assumptions as to the multipolarity of the 6.1-Mev transition. The possibilities are listed in the order of best agreement.

The spectra in Fig. 2 show the advantage of using internal pairs instead of external pairs for studying γ rays at good resolution. The yield of the internal pair lines is greater than that of the external pair lines, and the resolution of the internal and external lines are 2.3 and 3.5%, respectively. The resolution of the external lines is worse than the resolution of the internal lines, partly because of the energy spread in the converter and partly because a converter 7 mm in diameter was used for the external pair measurements, whereas the beam diameter for the internal pair measurements was 3 mm.

TABLE II. Possible multipolarities for the 6.7-Mev transition which are consistent with different assumptions as to the multipolarity of the 6.1-Mev transition.

Assumed multipolarity of 6.1-Mev γ ray	Possible multipolarities for 6.7-Mev γ ray[a]
$E1$	$E2$, $E1$, $M1$, $E3$
$E2$	$M1$, $E3$, $M2$, $E4$, $E2$
$M1$	$E4$, $M2$, $M3$, $E3$, $M1$, $M4$

[a] Listed in order of best agreement.

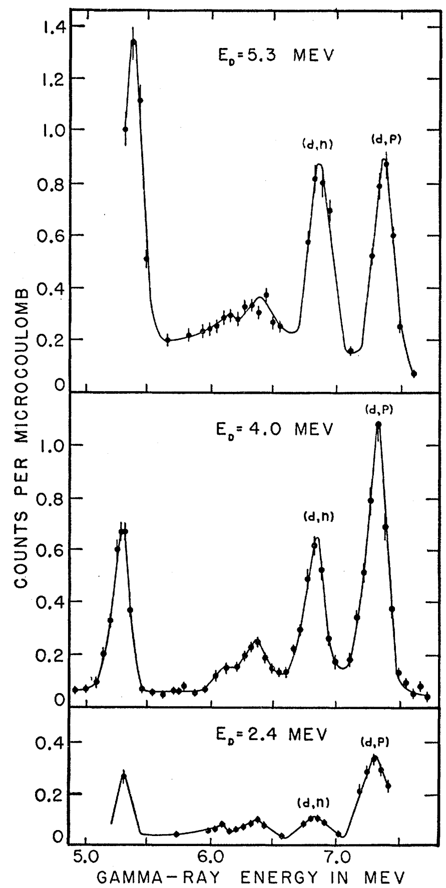

FIG. 3. Internal pair spectra from the bombardment of a 17 mg/cm² ZrN target with 2.4-, 4.0-, and 5.3-Mev deuterons. Spectrometer resolution = 2.5%.

IV. $N^{14}(d,p\gamma)N^{15}$ AND $N^{14}(d,n\gamma)O^{15}$

When N^{14} is bombarded with deuterons both the (d,p) and (d,n) reactions occur. The residual nuclei are the mirror pair, N^{15} and O^{15}. Since the decay schemes of mirror nuclei should be the same, the relative intensities of corresponding transitions in N^{15} and O^{15} are a measure of the relative (d,p) and (d,n) cross sections. Previous measurements of the γ rays from this reaction[2] showed that the 7.31-Mev γ ray from N^{15} and the 6.81-Mev γ ray from the mirror level in O^{15} are clearly resolved at 2.5% resolution. It was found, at 4.0-Mev bombarding energy, that the (d,p) cross section (average value, $E_d = 1.6$ to 4.0 Mev) to the 7.31-Mev state of N^{15} is 1.5 times larger than the (d,n) cross section to the 6.81-Mev state of O^{15}. The purpose of the present experiment was to investigate the relative (d,p) and (d,n) cross sections at two other bombarding energies.

Figure 3 shows the internal pair spectra obtained from the bombardment of a 17 mg/cm² ZrN target with 2.4-, 4.0-, and 5.3-Mev deuterons. A comparison of the intensities of lines at one bombarding energy with those at another bombarding energy can only be made with an accuracy of about 50% because of possible differences in the setting of the discriminator, which accepts the pulses from the coincidence circuit. The purpose of the experiment is to show how the relative intensities of the 7.31- and 6.81-Mev lines vary with bombarding energy. At 2.4-Mev bombarding energy, the line resulting from the (d,p) reaction is about 3 times more intense than the line resulting from the (d,n) reaction, whereas, at 5.3-Mev bombarding

TABLE III. Relative cross-sections for the reactions $N^{14}(d,p)^{*}N^{15}(7.31)$ and $N^{14}(d,n)^{*}O^{15}(6.81)$.

Bombarding energy (Mev)	$\frac{\sigma d,p}{\sigma d,n}$
2.4	2.6 ± 0.5[a]
4.0	1.5 ± 0.2[b]
5.3	0.9 ± 0.1[c]

[a] Average cross sections for $E_d = 0$ to 2.4 Mev.
[b] Average cross sections for $E_d = 1.6$ to 4.0 Mev.
[c] Average cross sections for $E_d = 4.1$ to 5.3 Mev.

energy the intensities of the two lines are about equal. This behavior is expected qualitatively on the basis of a stripping mechanism due to the effect of the Coulomb field. At low bombarding energies the (d,p) reaction is favored since the proton is repelled from the nucleus by the Coulomb field, whereas, at energies well above the Coulomb barrier this effect is negligible. Table III gives the ratio of the (d,p) cross section for producing N^{15} in the 7.31-Mev state to the (d,n) cross section for producing O^{15} in the mirror 6.81-Mev state for three different bombarding energies. These relative cross-sections were obtained from the peak heights of Fig. 3 by making corrections for the energy dependence of the efficiency of the spectrometer.

Because of the poor statistics and uncertainties in background corrections, a comparison of the relative intensities of the 6.33- and 6.12-Mev mirror lines cannot be made with significant accuracy.

The increase in intensity of the 5.3-Mev line at high-bombarding energies may be due to an increase in the population of high-excited states in N^{15} which cascade to the 5.3-Mev level.

PHYSICAL REVIEW VOLUME 100, NUMBER 3 NOVEMBER 1, 1955

Gamma Rays from the Deuteron Bombardment of Al^{27} and P^{31}†

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(Received June 15, 1955)

A magnetic-lens pair spectrometer has been used to study the radiations produced by the bombardment of Al^{27} and P^{31} with 4.6-Mev deuterons from The Rice Institute Van de Graaff accelerator. Gamma rays from the bombardment of Al^{27} were observed at 6.9 ± 0.1, 7.38 ± 0.06, 7.55 ± 0.06, 7.91 ± 0.04, 8.28 ± 0.04, 8.75 ± 0.04, 9.08 ± 0.04, 9.45 ± 0.08, 9.87 ± 0.08, and 10.7 ± 0.2 Mev. Gamma rays from the bombardment of P^{31} were observed at 4.41 ± 0.04, 4.71 ± 0.04, 4.94 ± 0.04, 5.29 ± 0.04, 5.79 ± 0.04, 6.11 ± 0.04, 6.84 ± 0.04, 7.46 ± 0.08, 8.16 ± 0.04, and 8.53 ± 0.04 Mev. All energies are doppler-corrected.

I. INTRODUCTION

INVESTIGATIONS using a magnetic lens pair spectrometer of the radiations produced by the deuteron bombardment of Li^7, Be^9, B^{10}, C^{12}, C^{13}, and F^{19}, the proton bombardment of B^{11}, F^{19}, and Ca^{40}, and the α-particle bombardment of Be^9 have been reported in earlier papers.[1–4] The results obtained from investigations of the γ rays produced by the deuteron bombardment of Al^{27} and P^{31} are presented in the present paper. The apparatus and experimental techniques used to make these measurements have been previously described.[1]

II. $Al^{27}+d$

The γ rays produced by the deuteron bombardment of Al^{27} were first investigated with 3.6% resolution using a ring focus spectrometer arrangement. The internal pair spectrum obtained from the bombardment of a 13.5 mg/cm² aluminum foil with 4.6-Mev deuterons is shown in Fig. 1, corrected for a zero magnetic field background equal to about 2% of the 7.5-Mev peak and an accidental rate equal to about 12% of this peak. Data were not taken below 7 Mev because of the large accidental rate caused by the beta rays from Al^{28}.

The region between 7 and 9.4 Mev was investigated further with 2.5% resolution using an intermediate image spectrometer arrangement. The results shown in Fig. 2 have been corrected for an accidental rate equal to about 10% of the 7.5-Mev peak. The zero magnetic field background was small. Data were not taken above 9.4 Mev because of power limitations.

In order to look for γ rays below 7 Mev, a 2.8-mm aluminum absorber was placed behind the target to reduce the energy of the beta rays from Al^{28}, and the

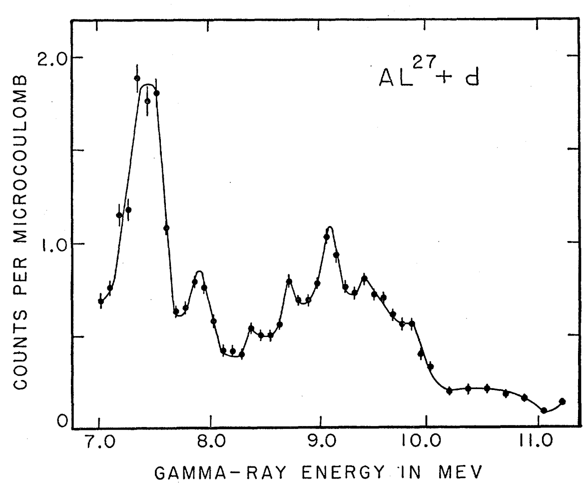

FIG. 1. Internal pair spectrum from the bombardment of a 13.5 mg/cm² aluminum foil with 4.6-Mev deuterons. Spectrometer resolution =3.6%.

† Supported in part by the U. S. Atomic Energy Commission.
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[1] Bent, Bonner, and Sippel, Phys. Rev. **98**, 1237 (1955).
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