The same situation seems to apply to the ground state of other odd–odd nuclides in this mass region. I^{124} and Sb^{122} exhibit an α-shape ground state spectrum. There is some indication that both I^{134} and I^{136} have a 2^- ground state. If the spin of Sb^{124} is 3^- as proposed, this again points to an $h_{11/2}$ state for the 73rd neutron while the proton may be in the $d_{5/2}$ state. The disintegration schemes of both I^{130} and I^{132} seem to require an odd-parity ground state.

Moreover, the even-even isotopes of Te and Xe in this mass region seem to possess at least a second 2^+ state at an excitation energy slightly larger than twice that of the first excited 2^+ state. This situation now has been found in Te^{122}, Te^{124}, Te^{126}, Xe^{126}, and Xe^{136}.

Nothing can be concluded about the occurrence of a 4^+ state in the energy region considered in Te^{126} and Xe^{126}, since these would not be populated to any considerable extent as estimated by the *ft*-value consideration.

ACKNOWLEDGMENTS

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Pair Spectrometer Measurements of the Radiations from Excited States of Light Nuceli*

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A magnetic-lens pair spectrometer has been used to study the radiations produced by the bombardment of certain light nuclei with protons and deuterons from a Van de Graaff accelerator. Gamma rays from the bombardment of F^{19} with 3.7-Mev protons were observed at 6.10±0.04 and 6.99±0.04 Mev. At 4.7-Mev bombarding energy, no lines were observed between 7.5 and 11.0 Mev with an intensity as great as 10 percent of that of the 6.99-Mev line. Gamma rays from the bombardment of C^{13} with 2.0-Mev deuterons were observed at 3.42±0.03, 3.71±0.05, 3.94±0.06, 4.48±0.04, 4.96±0.03, 5.12±0.04, 5.74±0.03, 6.14±0.03, 6.53±0.05, and 6.72±0.03 Mev. At 4.0-Mev bombarding energy, lines were observed at 6.14±0.03, 6.53±0.04, 6.72±0.03, 7.09±0.03, and 7.34±0.04 Mev. Gamma rays from the bombardment of C^{12} with 4.0-Mev deuterons were observed at 3.76±0.02 and 3.86±0.02 Mev. No lines were observed between 3.86 and 5.8 Mev with an intensity as great as 10 percent of that of the 3.86-Mev line. All the energies of γ rays given above are uncorrected for Doppler shifts which in some cases are as large as 40 kev. A search was made for nuclear pairs which might originate from the proton bombardment of B^{11}. No pairs were observed at 4.0-Mev bombarding energy in the energy range between 6.5 and 9.5 Mev. A search was also made for nuclear pairs which might result from the $Li^7(d,n)Be^8$ reaction. No pairs were observed in the energy range between 5.0 and 8.5 Mev.

I. INTRODUCTION

MEASUREMENTS of γ-ray energies greater than about 3 Mev can best be made by utilizing the pair production process since the probability for the production of pairs increases, whereas the Compton and photoelectric cross sections decrease, with increasing γ-ray energy. The work of Bame and Baggett,[1] Siegbahn and Johansson,[2] and Alburger[3] showed that the magnetic lens pair spectrometer was well suited for making such measurements and indicated that with further refinements this technique would be useful for studying complicated γ-ray spectra. The resolution of these earlier spectrometers was limited by low counting rates resulting from small solid angles and by large background effects due to accidental coincidences and real coincidences of scattered electrons, γ rays, and neutrons. It was apparent that in order to improve the resolution of these earlier instruments it would be necessary to improve the transmission to resolution ratio of the spectrometer and the resolving time and energy discrimination of the coincidence circuit.

The work of DuMond[4] indicated that the transmission to resolution ratio of the spectrometer used by Bame and Baggett[1] could be increased if a ring focus was employed and the average acceptance angle was increased to approximately 45°. To accomplish this the spectrometer was shortened and a small coil was added in the center of the spectrometer to create a fairly uniform field. Photographic techniques were used to locate the ring focus. The Geiger counters used by Bame and Baggett were replaced by scintillation detectors and the spectrometer was used in this form by Bent, Bonner, and Sippel.[5] Experiments were then

* Supported by the U. S. Atomic Energy Commission.
[1] S. J. Bame and L. M. Baggett, Phys. Rev. **79**, 415(A) (1950); Phys. Rev. **84**, 891 (1951).
[2] K. Siegbahn and S. Johansson, Rev. Sci. Instr. **21**, 442 (1950).
[3] D. E. Alburger, Rev. Sci. Instr. **23**, 671 (1952).
[4] J. W. M. DuMond, Rev. Sci. Instr. **20**, 160 (1949).
[5] Bent, Bonner, and Sippel, Phys. Rev. **91**, 472(A) (1953).

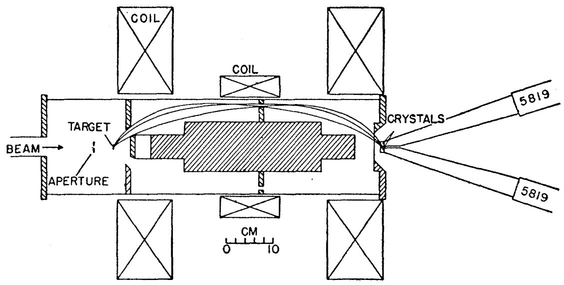

FIG. 1. Diagram of the pair spectrometer. The proton or deuteron beam from the Rice Institute 6-Mev Van de Graaff accelerator strikes the target after passing through a defining aperature 3 mm in diameter. The positron-electron pairs come to a focus outside of the vacuum chamber and are counted in coincidence with scintillation detectors.

performed to investigate an intermediate-image focusing principle similar to that used by Slätis and Siegbahn,[6] and Daniel and Bothe,[7] which resulted in the reduction of the aberration of the instrument and in the elimination of an unexplained "ghost image" which appeared with the ring focus spectrometer. The resolving time of the coincidence circuit was reduced to 2 millimicroseconds by using a coincidence detection system consisting of stilbene crystals, R.C.A. 5819 phototubes, and a fast coincidence circuit of the type described by Fischer and Marshall.[8]

With this improved spectrometer and coincidence detection system it became feasible to observe the γ spectra from a number of reactions in light nuclei with 2.5 percent energy resolution. The Rice Institute 6-Mev Van de Graaff accelerator was used to study a number of reactions at higher bombarding energies than previously.

II. APPARATUS

A. Spectrometer

A drawing of the spectrometer used in this work is shown in Fig. 1. The two large focusing coils are those which were used by Bame and Baggett in an earlier spectrometer.[1] They contain about 150 turns each of $\frac{3}{8}$-inch copper tubing which are cooled by water flowing through them. The small coil in the center contains 626 turns of solid $\frac{3}{32}$-inch copper wire. The vacuum chamber of the spectrometer is an 8-inch o.d. brass tube with $\frac{1}{8}$-inch wall. The acceptance baffles and intermediate ring baffle are made of aluminum $\frac{3}{8}$ inch thick and the central cylinder which shields the detectors from direct radiation from the source is made of lead. The inside of the brass tube and the outside of the central lead cylinder are lined with polyethylene to reduce the scattering of electrons. There are no iron parts in the spectrometer. The beam from the vertical 6-Mev Rice Institute Van de Graaff is bent through 90° by an analyzing magnet and enters the spectrometer horizontally. It then passes through a hole 3 mm in diameter in a tantalum sheet which is placed about 4 cm in front of the target. The electron pairs focused by the spectrometer pass through 10 mils of aluminum at the other end of the spectrometer and are detected outside of the vacuum chamber. The current supply and regulating equipment have been described by Bame and Baggett.[1] The center coil, in series with a variable resistor, is connected in parallel with the large coils so that the ratio between the current in the large coils and the current in the small center coil can be varied within limits. The whole spectrometer is surrounded by two Helmholtz coils which are used to cancel the component of the earths magnetic field which is perpendicular to the axis of the spectrometer. The optimum field gradient and the positions of the acceptance and intermediate ring baffles were determined by techniques similar to those described by Slätis and Siegbahn.[6] The dimensions of the spectrometer are as follows: Distance from center of first large coil to center of second large coil = 43.8 cm. Distance from target to center of first large coil = 6.7 cm. Distance from plane half-way between two large coils to intermediate ring baffle = 2.5 cm. Distance from crystals to center of second large coil = 5.5 cm. Distance from target to detectors = 56 cm. Outer radius of intermediate ring baffle = 9.0 cm. Average acceptance angle = 41°.

The optimum field gradient was obtained when the current in the center coil was 1/39 times the current in the large coils and opposite in direction to the current in the large coils. The magnitude of axial component of the magnetic field on the axis of the spectrometer at the center of the spectrometer was then 0.45 times its value at the center of one of the large coils. With a source 3 mm in diameter, an intermediate ring baffle 6 mm wide and an acceptance solid angle equal to 9 percent of the total sphere, the best resolution obtained with the Cs^{137} internal conversion line was 2.7 percent. 2.0 percent resolution was obtained with an acceptance solid angle equal to 4 percent of the total sphere and an intermediate ring baffle 3 mm wide. Improvements in transmission and resolution may result from better alignment. So far it has not been possible to make the resolution for positive and negative electrons quite optimum at the same time. The paths of positrons are simulated with a Cs source by changing the direction of the current in the coils. With this arrangement 33 kilowatts of power are needed to focus 4.2-Mev electrons, which corresponds to a γ-ray energy of 9.4 Mev. Measurements of higher γ-ray energies with this input power are planned by changing the geometry of the coils. Changes in the field shape resulting from two additional coils are expected to result in improved transmission and resolution.

The dc generator available for the spectrograph could not be used at a power level above 33 kw except for short periods of time. Thus with the preceding arrangements the experiments were limited to a study of

[6] H. Slätis and K. Siegbahn, Arkiv Fysik **1**, 339 (1949).
[7] H. Daniel and W. Bothe, Z. Naturforsch. **9a**, 402 (1954).
[8] J. Fischer and J. Marshall, Rev. Sci. Instr. **23**, 417 (1952).

γ radiation with energies less than 9.4 Mev. In order to be able to look for γ rays with energies greater than 9.4 Mev the center coil of the spectrometer was connected so that the current in this coil was in the same direction as the current in the two large coils, the intermediate image baffles and the acceptance baffles were removed, and a ring baffle 1.8 cm wide was placed 4.1 cm from the exit foil of the spectrometer. The correct position and size of the ring baffles were determined by photographic techniques. The resolution of the O^{16} nuclear pair line with this spectrometer arrangement was 3.6 percent.

B. Coincidence Detection System

The requirements of the coincidence detection system are that it have a short time resolution in order that the accidental coincidence rate be small, and that it have some energy discrimination to make possible the reduction of true coincidences due to scattered electrons, γ rays, neutrons, and annihilation radiation.

Stilbene crystals $\frac{3}{4}$ inch in diameter and of differing thicknesses were used for detection. The crystal thickness was chosen so that the electrons focused by the spectrometer would lose most of their energy in the crystals. The crystals were connected to photomultiplier tubes with lucite rods which were 12 inches long and the photomultipliers were magnetically shielded. Negative pulses from the photomultipliers were fed to the grids of *6AG7s*, cutting the tubes off. Positive pulses were taken from the plates of the *6AG7s* and fed to a *6BN6* coincidence circuit of the type described by Fischer and Marshall.[8] The pulses were clipped at the input of the coincidence circuit with shorted stubs. The time resolution of this type of coincidence circuit is about equal to the width of the pulses which are fed into it. With 10-inch clipping stubs the resolving time (half-width at the half-height of a delay curve) was 2×10^{-9} seconds. Most of the data were taken, however, with a resolving time of 10^{-8} seconds. The output of the coincidence circuit goes to an amplifier then to a pulse-height discriminator and a scalar. Since the output pulse size of the coincidence circuit is a rapidly varying function of the input pulse sizes, the pulse-height discriminator could be used to prevent the counting of true coincidences due to pulses in the crystals which were smaller than the pulses due to the pairs focused by the spectrometer.

III. PROCEDURE

In most of the experiments internal pairs produced in the product nuclei of the reactions were observed. The probability of this process is low, but all these pairs from a certain excited state have the same energy except for Doppler broadening. If external pairs produced in a heavy radiator are used, an extra spread in the pair energy results from the radiator thickness. For an energy resolution for γ radiation of about 5 percent or greater, the use of an external radiator to produce pairs gives a higher intensity than is obtained with internal pairs. When higher resolution is wanted, the internal pairs will give more intensity.

The use of an external radiator is also useful in reactions where high-intensity β emitters are formed in the target. In cases of this type, the chance coincidences of the β particles may be prohibitive, requiring the use of an absorber of low atomic number to stop the β rays and then a heavy radiator as a source of external pairs.

Three types of background tend to obscure weak γ-ray peaks. The accidental coincidence rate is measured by inserting a long piece of cable in one side of the coincidence circuit. A second type of background results from single high-energy electrons producing pulses in both crystals. This background is minimized by placing a tungsten sheet, 1.5 mm thick, between the two crystals, and by biasing to exclude annihilation photons. A third background is due to the scattering of high-energy γ rays and neutrons from the walls and coils of the spectrometer and can be minimized by using small crystals for detection, biased to accept the largest pulses. An approximate determination of this effect is obtained by measuring the coincidence rate with zero current in the spectrometer coils.

In order to count the coincidences due to the positron-electron pairs and to exclude as many background pulses as possible, the crystal thickness was generally chosen so that the pairs would lose nearly all of their energy in the crystals. If the crystals are thick enough to stop the electrons focused by the spectrometer, the pulse size varies with the energy of these electrons, and hence the discriminator must be varied to give constant detection efficiency for γ radiation of different energies. In order to avoid this complication, thinner crystals can be used where background effects are small. The pulse size then is about the same for all electrons which pass through the crystals. Usually crystals $\frac{1}{4}$ inch thick were used for γ-ray energies between 3 and 7 Mev, crystals $\frac{3}{8}$ inch thick were used for the region between 7 and 9 Mev, and crystals $\frac{1}{2}$ inch thick were used between 9 and 11 Mev.

Geiger and scintillation counters were used to monitor the γ radiation from the target. Also, the total beam striking the target was measured with a microammeter so that approximate γ-ray yields could be calculated. The efficiency of the pair spectrometer for detecting γ rays of different energies was determined by comparing the pair yields obtained with this spectrometer from the $C^{13}+D$, and $B^{10}+D$ reactions with the absolute γ-ray yields given for these reactions by Baggett and Bame,[9] Thomas and Lauritsen,[10] and Terrell and Phillips.[11] Because of uncertainties in background corrections and in detection efficiencies, and since the multipole order of the radiation is in general

[9] L. M. Baggett and S. J. Bame, Phys. Rev. **84**, 154 (1951).
[10] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).
[11] J. Terrell and G. C. Phillips, Phys. Rev. **83**, 703 (1951).

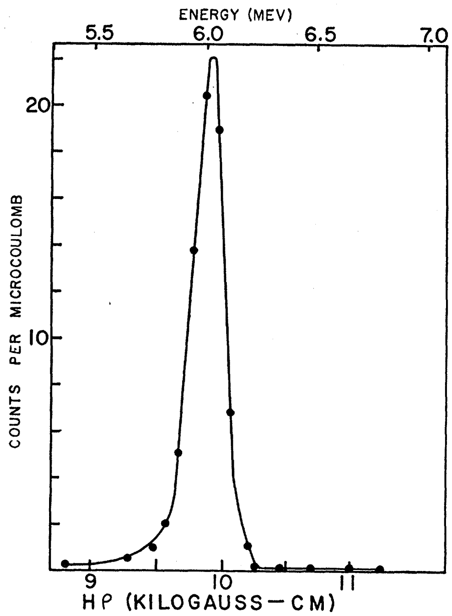

FIG. 2. The 6.05-Mev nuclear pair line from the bombardment of a 3.98-mg/cm² CaF_2 target with 2.0-Mev protons. Spectrometer resolution: 2.5 percent.

not known, the relative γ-ray yields for some of the weak lines are only accurate to within a factor of 2 and the absolute values to within a factor of 3 or 4.

The 6.055±0.015 Mev nuclear pair line from O^{16*} was used for energy calibration of the instrument in terms of the current. The γ-ray energies were determined from the values of the current at the positions of the peaks. The errors of the γ-ray energies include errors in picking the position of the O^{16} pair peak, in the knowledge of the energy of the O^{16} pair-emitting state, in the determination of target thicknesses, and in picking the positions of the peaks from the spectra. Most of the error is due to uncertainties in picking the peak positions from the spectra.

The positions and shapes of the pair lines obtained are affected by the motion of the radiating nucleus if

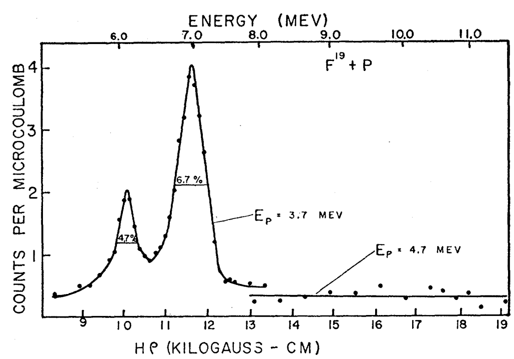

FIG. 3. The external pair spectrum from the bombardment of a thick CaF_2 target with 3.7- and 4.7-Mev protons. A 61-mg/cm² lead converter was separated from the target by 3 mm of aluminum. Spectrometer resolution: 4.0 percent.

the excited nucleus radiates before coming to rest in the target material (see Thomas and Lauritsen[10]). Corrections have been listed only for the maximum possible Doppler shift due to the center-of-mass motion, and an additional error has been added to the Doppler-corrected γ-ray energies to allow for the possible effects of the angular distribution of the radiating nuclei which in most cases is unknown.

IV. RESULTS AND DISCUSSION

A. $F^{19}+H^1$

Because of the large intensity of the nuclear pairs emitted from the first excited state of O^{16}, the $F^{19}(p,\alpha\pi)O^{16}$ reaction has been used extensively both for testing the performance of the pair spectrometer and for energy calibration. The target was 3.98 mg/cm² of CaF_2 evaporated onto a 11.8-mg/cm² copper foil. The nuclear pair line observed at 2.0-Mev bombarding energy with 2.5 percent resolution is shown in Fig. 2.

The γ radiations from the reaction $F^{19}(p,\alpha)O^{16*}$ were observed with an external radiator. Such an arrange-

TABLE I. Energies and yields of the γ rays from the bombardment of a thick CaF_2 target with 3.7-Mev protons.

Uncorrected energy (Mev)	Doppler-corrected energy (Mev)	Yield (γ/proton) ×10⁶	Total cross section[a] (mb)	Assignment (Mev)	Reference
6.10±0.04	6.08±0.05	1.3	2.7	O^{16}(6.14)	14
6.99±0.04	6.97±0.05	1.8	3.7	O^{16}(6.91) (7.12) unresolved	14

[a] Average value, $E_p=0$ to 3.7 Mev.

ment was needed to prevent the strong nuclear pair line from obscuring the γ rays. The thick CaF_2 target was backed by 3 mm of aluminum and a lead converter which had a mass of 61 mg/cm². The results obtained at 3.7- and 4.7-Mev bombarding energy are shown in Fig. 3, uncorrected for background effects. The energies of the two lines were calculated assuming that each external pair peak was shifted down by an amount equal to the most probable energy lost by a single electron in passing through the 61-mg/cm² lead converter. This shift was calculated to be 0.12 Mev. The energies of the γ rays and the cross sections for their production are given in Table I. No lines were seen between 7.5 and 11.0 Mev with an intensity greater than 10 percent of that of the 6.99-Mev peak.

DISCUSSION

These results are in agreement with those obtained in several other measurements of the γ rays resulting from the $F^{19}(p,\alpha)O^{16*}$ reaction[3,12,13] except that in

[12] R. L. Walker and B. D. McDaniel, Phys. Rev. 74, 315 (1948).
[13] Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. 77, 617 (1950).

previous measurements the 6.1-Mev line was always more intense than the 7.0-Mev peak. It was shown by Walker and McDaniel[12] that the 7.0-Mev radiation became more intense relative to the 6.1-Mev line as the bombarding energy was increased from 0.45 to 1.15 Mev. Table II gives the ratio of the intensities of these two peaks at different bombarding energies.

The 6.10±0.04 Mev γ-ray energy is less than the 6.14-Mev energy of the O^{16*} as determined from measurements of particle groups.[14] If the maximum Doppler shift of 0.02 Mev is subtracted from the γ-ray measurement, the disagreement is made worse. This is an indication that the 6.10-Mev γ ray is emitted after the radiating nucleus loses most of its velocity in the target material (i.e., after $\sim 10^{-13}$ second). Radiation from this 3^- level in O^{16} to the 0^+ ground state is expected to be relatively slow ($\sim 10^{-10}$ second).

There are several possible explanations for the absence of γ rays with energies greater than 7 Mev in addition to the possibility that they may have been too weak to be observed. If the states in O^{16} in this region have even parity and even angular momentum or odd

TABLE II. Ratio of the intensities of the 7.0- and 6.1-Mev γ rays from the $F^{19}+p$ reaction at different bombarding energies. Data 0.45 to 1.15 Mev from Walker and McDaniel, 3.7-Mev data present experiment.

Bombarding energy (Mev)	Intensity of 7.0-Mev γ rays / Intensity of 6.1-Mev γ ray
0.45	0.043
0.70	0.17
1.15	0.38
3.7	1.4

parity and odd angular momentum they would break up into $C^{12}+\alpha$ much faster than they could emit γ radiation. Also, if the states have high angular momenta ($\gtrsim 2$), then transitions to the 6.1-, 6.9- or 7.1-Mev states would be expected to be more probable than transitions to the ground state.

B. $C^{13}+H^2$

A 48 percent C^{13} target was made by cracking methyl iodide onto a hot strip of tungsten. Flakes of carbon approximately 4 mg/cm² thick were then removed from the tungsten strip and mounted onto a 9.2-mg/cm² copper foil. The internal pair spectrum obtained at 2.0-Mev bombarding energy is shown in Fig. 4. A zero-current background which was about 50 percent of the lowest points and an accidental-coincidence rate which was about 10 percent of the lowest points has been subtracted from the original data. The high-energy region of the spectrum observed at 4.0-Mev bombarding energy is shown in Fig. 5, uncorrected for background

[14] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 24, 321 (1952).

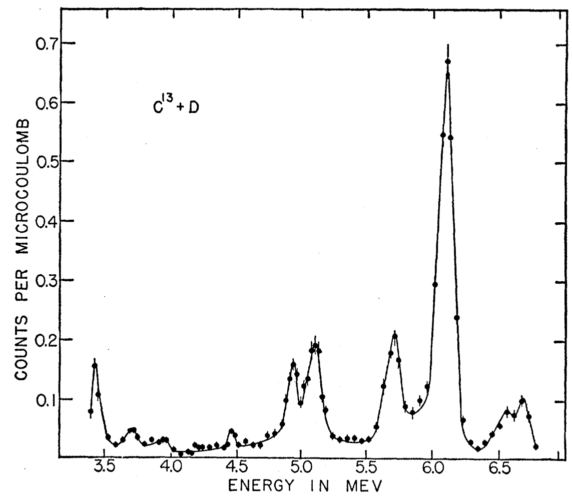

FIG. 4. The internal pair spectrum from the bombardment of a 4-mg/cm² carbon target (48 percent C^{13}) with 2.0-Mev deuterons. Spectrometer resolution: 2.5 percent.

effects. At 4.0-Mev bombarding energy, additional data were taken up to a γ energy of 8.6 Mev, but no lines were observed between 7.5 and 8.6 Mev with an intensity as great as 5 percent of that of the 6.1-Mev line. The resolution of all well-resolved lines in Figs. 4 and 5 is 2.5 percent. The γ-ray energies and yields are given in Table III.

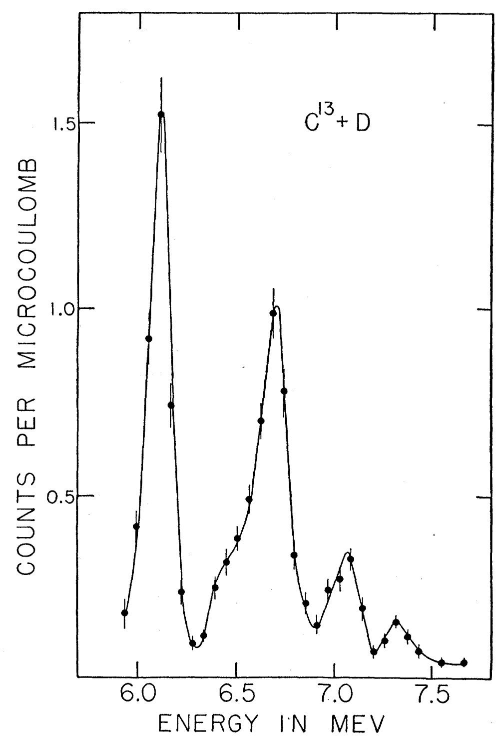

FIG. 5. The internal pair spectrum from the bombardment of a 4-mg/cm², 48 percent C^{13} target with 4.0-Mev deuterons. Spectrometer resolution: 2.5 percent.

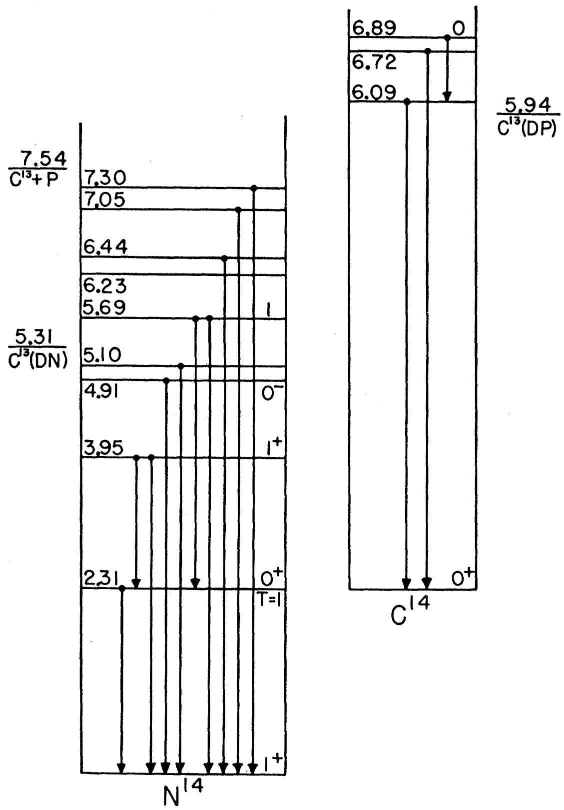

FIG. 6. Energy levels of N^{14} and C^{14} and the γ rays from $C^{13}+H^2$.

DISCUSSION

Gamma rays from the deuteron bombardment of C^{13} have been reported at 3.05, 3.40, 5.04, and 6.10 Mev by Baggett and Bame,[9] at 3.08, 3.39, 5.05, 5.69, and 6.11 Mev by Thomas and Lauritsen,[10] and at 3.91, 4.93, 5.13, 5.73, 6.12, 6.45, and 6.73 Mev by Mackin, Mims, and Mills.[15] The 3.71-, 4.48-, 7.09-, and 7.34-Mev γ rays have not been previously observed. There is no indication of a strong 4.1-Mev line which would be expected if there was a nuclear pair-emitting state in C^{14} at this energy.[10]

When C^{13} is bombarded with deuterons the following reactions, which could account for the γ rays, occur.

$$C^{13}(d,n)N^{14} \qquad Q=5.31 \text{ Mev},$$
$$C^{13}(d,p)C^{14} \qquad Q=5.94 \text{ Mev},$$
$$C^{13}(d,\alpha)B^{11} \qquad Q=5.16 \text{ Mev}.$$

The 6.14- and 6.72-Mev γ rays are assigned to C^{14} since they correspond to recently observed levels[16] in C^{14}. The 7.34-Mev line is probably due to an excited state in N^{14} since no proton groups were observed from the (d,p) reaction corresponding to a level in C^{14} at this energy. The 7.09-, 6.53-, 5.74-, 5.12-, and 4.96-Mev lines are all assigned to N^{14} since they correspond to ground-state transitions from known states in N^{14}. The 3.42-Mev line is probably due to a transition between the 5.69- and 2.31-Mev states in N^{14}. The 3.71- and 3.94-Mev lines are probably from excited states in C^{13}, resulting from the $C^{12}(d,p)C^{13}$ reaction; both the intensities and energies are consistent with this assignment. The 3.94-Mev γ ray could also be from N^{14}. A definite assignment for the 4.48-Mev line cannot be made. The energy agrees well with the 4.46-Mev state in B^{11}, however, the intensity of the line is greater than would be expected in view of the failure of Thomas and Lauritsen[10] to detect a 2.14-Mev γ ray from the $C^{13}(d,\alpha)B^{11*}$ reaction. It seems unlikely that a 4.46-Mev state in N^{14} would have escaped detection by Bockelman, Browne, Buechner, and Sperduto,[17] or by Benenson.[18] It may be that this line is due to a ground-state transition from a 4.46-Mev state in C^{14} since apparently no experiment has been performed which would eliminate this possibility. The line could also be due to a transition from a state at 6.77 Mev in N^{14} to the 2.31-Mev state.

At 7.0-Mev bombarding energy, the proton group corresponding to the level in C^{14} at 6.9 Mev has been observed with an intensity about equal to the intensity of the group leaving C^{14} in the 6.72-Mev state.[16] The fact that no 6.9-Mev γ ray was observed with an intensity greater than 10 percent of the intensity of the 6.7-Mev γ ray indicates that the 6.9-Mev level probably cascades to the 6.1-Mev level.

TABLE III. Energies and yields of the γ rays from the bombardment of a 4-mg/cm² 48 percent C^{13} target with 2.0- and 4.0-Mev deuterons.

Uncorrected energy (Mev)	Doppler-corrected energy (Mev)	Yield (γ/deut) $\times 10^6$	Total cross section (mb)	Assignment (Mev)	Reference
$E_d=2.0$ Mev			a		
6.73±0.03	6.70±0.04	0.38	4.1	$C^{14}(6.72)$	16
6.52±0.05	6.49±0.06	0.31	3.3	$N^{14}(6.43)$	18
6.14±0.03	6.11±0.04	2.3	25	$C^{14}(6.09)$	16
5.74±0.03	5.72±0.04	0.84	9.1	$N^{14}(5.69)$	19
5.12±0.04	5.10±0.05	1.0	11	$N^{14}(5.10)$	17
4.96±0.03	4.94±0.04	0.90	9.7	$N^{14}(4.91)$	17
4.48±0.04	4.46±0.05	0.32	3.5	$B^{11}(4.46)$, C^{14}, or N^{14}(Cascade)	14
3.94±0.06	3.92±0.07	0.31	3.3	$C^{13}(3.86)$ or $N^{14}(3.95)$	16 17
3.71±0.05	3.69±0.06	0.49	5.3	$C^{13}(3.68)$	16
3.42±0.03	3.41±0.04	1.8	19	N^{14}(Cascade 5.69→2.31)	
$E_d=4.0$ Mev			b		
7.34±0.04	7.30±0.05	0.29	3.1	$N^{14}(7.50?)$	18
7.09±0.03	7.05±0.04	0.76	8.2	$N^{14}(7.00)$	18
6.72±0.03	6.68±0.04	2.4	26	$C^{14}(6.72)$	16
6.53±0.04	6.49±0.05	0.9	9.7	$N^{14}(6.43)$	18
6.14±0.03	6.10±0.04	4.8	52	$C^{14}(6.09)$	16

a Average value, $E_d=1.0$ to 2.0 Mev.
b Average value, $E_d=3.4$ to 4.0 Mev.

15 Mackin, Mims, and Mills, Phys. Rev. **93**, 950(A) (1954).
16 Sperduto, Buechner, Bockelman, and Browne, Phys. Rev. **96**, 1316 (1954).
17 Bockelman, Browne, Buechner, and Sperduto, Phys. Rev. **92**, 665 (1953).
18 R. E. Benenson, Phys. Rev. **90**, 420 (1953).

By comparing the γ-ray energies with the energies that would be expected from other experiments, it should be possible to tell whether or not Doppler shifts occur. Because of the experimental errors it is not possible to say anything definite about this. However, it is noted that, except for the 6.72-Mev line, the Doppler-corrected energies are in better agreement with other experiments than are the uncorrected values.

Energy level diagrams of N^{14} and C^{14} showing the γ rays from $C^{13}+D$ are shown in Fig. 6. The energies of the 2.31, 3.95, 4.91, and 5.10-Mev levels have been accurately measured by Bockelman, Browne, Buechner, and Sperduto from the inelastic scattering of protons and deuterons on N^{14}.[17] The energy of the 5.69-Mev level has been accurately measured by Cook, Marion, and Bonner[19] from a neutron threshold measurement. The energies of the 6.23- and 6.44-Mev states are due to Benenson.[18] The 7.05- and 7.30-Mev values are from the present γ-ray measurements. Spin and parity assignments are given which are consistent with the present γ-ray measurements and with measurements of the γ rays from the $C^{13}(p,\gamma)N^{14}$ reaction,[20–22] together with the neutron angular distributions of Benenson.[18] The 1.64- and 2.31-Mev γ rays were not observed in the present work but have been reported by Thomas and Lauritsen.[10] The energy levels of C^{14} have been accurately determined by the magnetic analysis of the proton groups from the $C^{13}(d,p)C^{14}$ reaction.[16] The cascade transition between the 6.89- and 6.09-Mev levels is inferred from the present experiment from the absence of 6.89-Mev γ radiation; recently a 0.811-Mev γ ray has been observed by Mackin and Mills,[23] which confirms this conclusion. An angular momentum of zero is assigned to the 6.89-Mev level to account for the absence of the ground state transition from this level.

C. $C^{12}+H^2$

A 57.8 mg/cm² graphite target was bombarded with 4.0-Mev deuterons and the internal pair spectrum was observed with 2.5 percent resolution. The results shown in Fig. 7 have been corrected for a zero-current background which was about 10 percent of the 3.86-Mev peak and for a chance coincidence rate which was about 5 percent of the 3.86-Mev peak. The slow rise in the counting rate above 5 Mev is probably an increase in background due to the fact that the discriminator bias accepting the pulses from the coincidence circuit was not increased rapidly enough as the pulse size increased. The spectrum shows two peaks corresponding to γ rays with energies of 3.76±0.02 and 3.86±0.02 Mev, uncorrected for Doppler effects. No lines were observed between 3.9 and 5.8 Mev with an intensity as great as 10 percent of that of the 3.86-Mev γ ray. The results are summarized in Table IV.

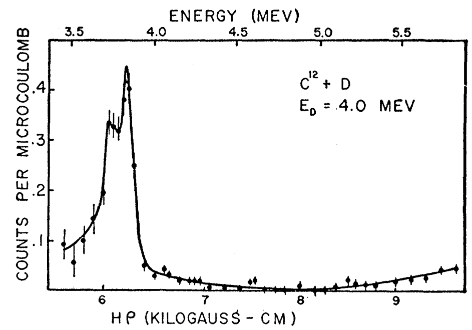

FIG. 7. The internal pair spectrum from the bombardment of a 57.8-mg/cm² carbon target with 4.0-Mev deuterons. Spectrometer resolution: 2.5 percent.

TABLE IV. Energies and yields of the γ rays from the bombardment of a thick graphite target with 4.0-Mev deuterons.

Uncorrected energy (Mev)	Doppler-corrected energy (Mev)	Yield (γ/deut) ×10⁶	Total cross section[a] (mb)	Assignment (Mev)	Reference
3.76±0.02	3.74±0.03	3.5	4.0	C^{13}(3.68)	16
3.86±0.02	3.84±0.03	4.0	4.5	C^{13}(3.85)	16

[a] Average value, $E_d=0$ to 4.0 Mev.

DISCUSSION

The 3.76- and 3.86-Mev γ-ray lines are assigned to C^{13} since it is energetically impossible to get γ rays of this energy from the (d,n) and (d,α) reactions. The energies of these levels have been reported by Sperduto *et al.*[16] to be 3.684±0.01 and 3.855±0.01 Mev. The γ-ray energy of 3.74 Mev disagrees with the 3.683-Mev energy of C^{13*} by more than the estimated experimental error; however, no other interpretation of this γ ray has been suggested.

It has been reported by Rotblat[24] and Sperduto *et al.*[16] that at ~8-Mev bombarding energy the proton group leaving C^{13} in the 3.68-Mev state is much weaker than the proton group leaving C^{13} in the 3.86-Mev state. The fact that the γ rays corresponding to transitions to the ground state from the 3.68- and 3.86-Mev states are of about equal intensity suggests that a cascade transition takes place between the 3.86-Mev level and the 3.68-Mev level. This interpretation is in agreement with other measurements of the γ rays from the $C^{12}(d,p)C^{13*}$ reaction[25] and with measurements of the γ rays from the $B^{10}(\alpha,p)C^{13*}$ reaction.[26,27] An energy level diagram summarizing the results is shown in Fig. 8.

[19] Cook, Bonner, and Marion, Phys. Rev. **95**, 639(A) (1954); and private communication.
[20] Woodbury, Day, and Tollestrup, Phys. Rev. **92**, 1199 (1953).
[21] Hicks, Husain, Sanders, and Beghian, Phys. Rev. **90**, 163 (1953).
[22] Hird, Whitehead, Butler, and Collie, Phys. Rev. **96**, 702 (1954).
[23] R. J. Mackin and W. R. Mills (private communication).
[24] J. Rotblat, Phys. Rev. **83**, 1271 (1951).
[25] R. J. Mackin, Jr., Phys. Rev. **92**, 529(A) (1953).
[26] Shire, Wormald, Lindsay-Jones, Lunden, and Stanley, Phil. Mag. **44**, 1197 (1953).
[27] A. G. Stanley, Phil. Mag. **45**, 430 (1954).

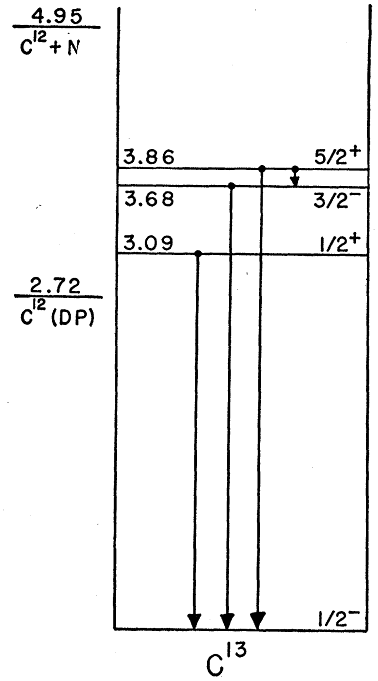

FIG. 8. Energy levels and decay scheme of C^{13}.

D. $B^{11}+H^1$ and Li^7+H^2

Phillips, Cowie, and Heydenburg[28] observed a soft radiation when B^{11} was bombarded with 7.9-Mev protons, which they suggested might be due to nuclear pairs from an odd-parity zero-angular-momentum level at about 7 Mev in Be^8. Other investigations[29–32] suggest that this soft radiation may have been due to a level in C^{12} of zero spin and even parity. The purpose of this experiment was to look for possible nuclear pairs from excited states in C^{12} and Be^8.

In order to have the greatest intensity in these experiments, they were carried out with the acceptance baffles, shown in Fig. 1, completely removed and with an intermediate-image ring baffle 2.7 cm wide. With this geometry the resolution of the Cs^{137} internal conversion line was 13 percent and the intensity of the line was 2.5 times greater than with the geometry shown in Fig. 1. The resolution of the O^{16} nuclear pair line was 5.5 percent and the intensity of this line was 10 times greater than that obtained with 2.5 percent resolution.

[28] Phillips, Cowie, and Heydenburg, Phys. Rev. **83**, 1049 (1951).
[29] G. Harries and W. T. Davies, Proc. Phys. Soc. (London) **A65**, 564 (1952).
[30] Beghian, Halban, Husain, and Sanders, Phys. Rev. **90**, 1129 (1953).
[31] Dunbar, Pixley, Wenzel, and Whaling, Phys. Rev. **92**, 649 (1953).
[32] G. Harries, Proc. Phys. Soc. (London) **A67**, 153 (1954).

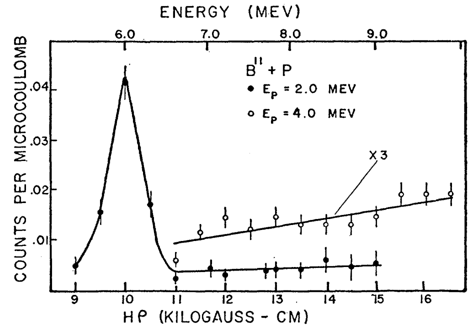

FIG. 9. The internal pair spectrum from the bombardment of a 19-mg/cm² natural boron target with 2.0- and 4.0-Mev protons. The 6.0-Mev peak is attributed to fluorine contamination. Spectrometer resolution: 5.5 percent.

The internal pair spectrum resulting from the bombardment of a 19-mg/cm² natural boron target at 2.0 and 4.0 Mev is shown in Fig. 9, uncorrected for background effects. The counts between 7 and 9 Mev were mostly due to the zero-current background. The chance rate was about 3 percent of this background.

DISCUSSION

The curve shows a peak at 6.04 Mev which is presumably due to fluorine contamination either in the boron or in the glyptal used to stick the thick powdered boron to the copper foil. This conclusion follows since the energy is the same, and the intensity of the line is 2700 times weaker than the intensity of the line resulting from the proton bombardment of a thick CaF_2 target with 2.0-Mev protons. An upper limit for the total cross section (average value, $E_p=1.7$ to 4.0 Mev) for the production of nuclear pairs in the energy range between 6.5 and 9.5 Mev is 3×10^{-5} mb.

A search was also made for nuclear pairs which might result from the $Li^7(d,n)Be^{8*}$ reaction by bombarding lithium targets with 330-kev deuterons. This low bombarding energy was used to minimize the amount of Li^8 produced in comparison to the amount of Be^8. No pairs were observed in the energy range between 5.0 and 8.5 Mev. An upper limit for the total cross section (average value, $E_d=0$ to 330 kev) is 2×10^{-5} mb.