Gamma Radiation from $Al^{27}+p$ and $F^{19}+p$*

W. A. RANKEN, T. W. BONNER, R. CASTILLO-BAHENA, M. V. HARLOW, JR., AND T. A. RABSON
The Rice Institute, Houston, Texas
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Gamma radiations with energies less than 3 Mev have been observed with an intermediate-image lens spectrometer when targets of aluminum and fluorine were bombarded by protons. Gamma-ray spectra from $Al+p$ were obtained for proton energies of 2.4, 3.0, 4.0, and 4.4 Mev. Gamma radiation with quantum energies of 0.845, 1.014, 1.722, 2.216, and 2.992 Mev were observed and are attributed to excited states of Al^{27}. Gamma radiations of 1.369 Mev from Mg^{24} and 2.741 Mev, probably from both Al^{27} and Mg^{24}, were also observed. Internal conversion electrons from the excited states of Al^{27} were observed; the conversion coefficients indicate that the 0.845-Mev radiation is $E2$ and that the 1.014-Mev radiation is $M1$. Gamma radiation from $F^{19}+p$ was observed with quantum energies of 1.236, 1.358, and 1.46 Mev. The relative intensities of the γ rays were observed for proton energies of 3.22, 3.65, and 4.27 Mev.

INTRODUCTION

THE utilization of the photoelectric effect in conjunction with a magnetic lens spectrometer provides a method of determining the energies and intensities of low-energy (below 3-Mev) γ radiation with good resolution and a considerable degree of accuracy. A comprehensive account of the techniques involved in photoelectric spectroscopy has been presented by Thomas and Lauritsen.[1] In the present work this method has been used to observe γ radiation, in the energy range of 0.4 to 3.0 Mev, produced by the bombardment of Al^{27} and F^{19} by protons.

The intermediate-image magnetic-lens spectrometer used to make these measurements has served in the past as a pair spectrometer and has been described previously.[2,3] The conversion of the pair spectrometer to a photoelectron spectrometer consists simply of replacing the coincidence detection system of the former by a single scintillation counter, comprised of a small cylindrical plastic scintillating element mounted on a tapered Lucite light pipe 20 inches in length. The light pipe is required to transmit light from the focal point of the spectrometer, a region of high magnetic field intensity, to a relatively field-free region where the photomultiplier tube used to detect the scintillations can operate effectively. Pulses from the photomultiplier are amplified and displayed on a 20-channel pulse-height analyzer. The scintillating elements are generally made thick enough to stop the photoelectron, since the greater pulse-height resolution achieved by this arrangement provides better separation of the true pulses from background pulses.

$Al^{27}+p$

A. Photoelectron Spectra

Gamma radiation from low-energy states in Al^{27} populated by the inelastic scattering of neutrons has been investigated by several research workers[4–6] using scintillation counters. The energies of these low-lying states have been accurately measured by magnetic[7,8] and electrostatic[9] analysis of inelastically scattered proton groups.

The results of the neutron experiments show quite different possible decay schemes for some of these levels. The present experiment was undertaken to obtain more accurate data as to the γ radiation from the levels in Al^{27}.

Gamma rays produced by the bombardment of a 0.85 mg/cm² Al^{27} target with protons were observed for proton bombarding energies of 2.4, 3.0, 4.0, and 4.4 Mev. The aluminum was evaporated directly onto a 17.7-mg/cm², $\frac{7}{8}$-inch square thorium foil in the belief that the close proximity of the aluminum to the converter would limit the effective size of the photoelectron source to something only slightly larger than the 2-mm beam spot. That this proved to be the case is shown by the fact that the resolution obtained for the spectrometer for photoelectrons from a thin converter was

TABLE I. Energies and assignments of γ rays from the reactions $Al^{27}(p,p')$ and $Al^{27}(p,\alpha)Mg^{24}$.

E_γ (Mev) (observed	E_γ (Mev) (Doppler-corrected)	Assignment	Level difference (Mev)[a,b]	Type of transition
0.845±0.005		Al^{27} 0.842 → 0	0.842	$E2$
1.017	1.014±0.007	Al^{27} 1.013 → 0	1.013	$M1$
1.3687[c]	...	Mg^{24} 1.3687 → 0	1.3687	$E2$
1.727	1.722±0.010	Al^{27} 2.732 → 1.013	1.719	$M1$ or $E1$
2.222	2.216±0.010	Al^{27} 2.213 → 0	2.213	
2.749	2.741±0.015	{Al^{27} 2.732 → 0	2.732	$E1$
		{Mg^{24} 4.122 → 1.369	2.753	$E2$
3.000	2.992±0.015	Al^{27} 3.001 → 0	3.001	

[a] See reference 7.
[b] See reference 11.
[c] Calibration line.

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[1] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).
[2] Bent, Bonner, and Sippel, Phys. Rev. **98**, 1237 (1955).
[3] Ranken, Bonner, McCrary, and Rabson, Phys. Rev. **109**, 917 (1958).
[4] R. R. Day, Phys. Rev. **102**, 767 (1956).
[5] I. L. Morgan, Phys. Rev. **103**, 1031 (1956).
[6] Rothman, Hans, and Mandeville, Phys. Rev. **100**, 83 (1955).
[7] Browne, Zimmerman, and Buechner, Phys. Rev. **96**, 725 (1954).
[8] Porter, Rothman, and Van Patter, Bull. Am. Phys. Soc. Ser. II, **2**, 143 (1957).
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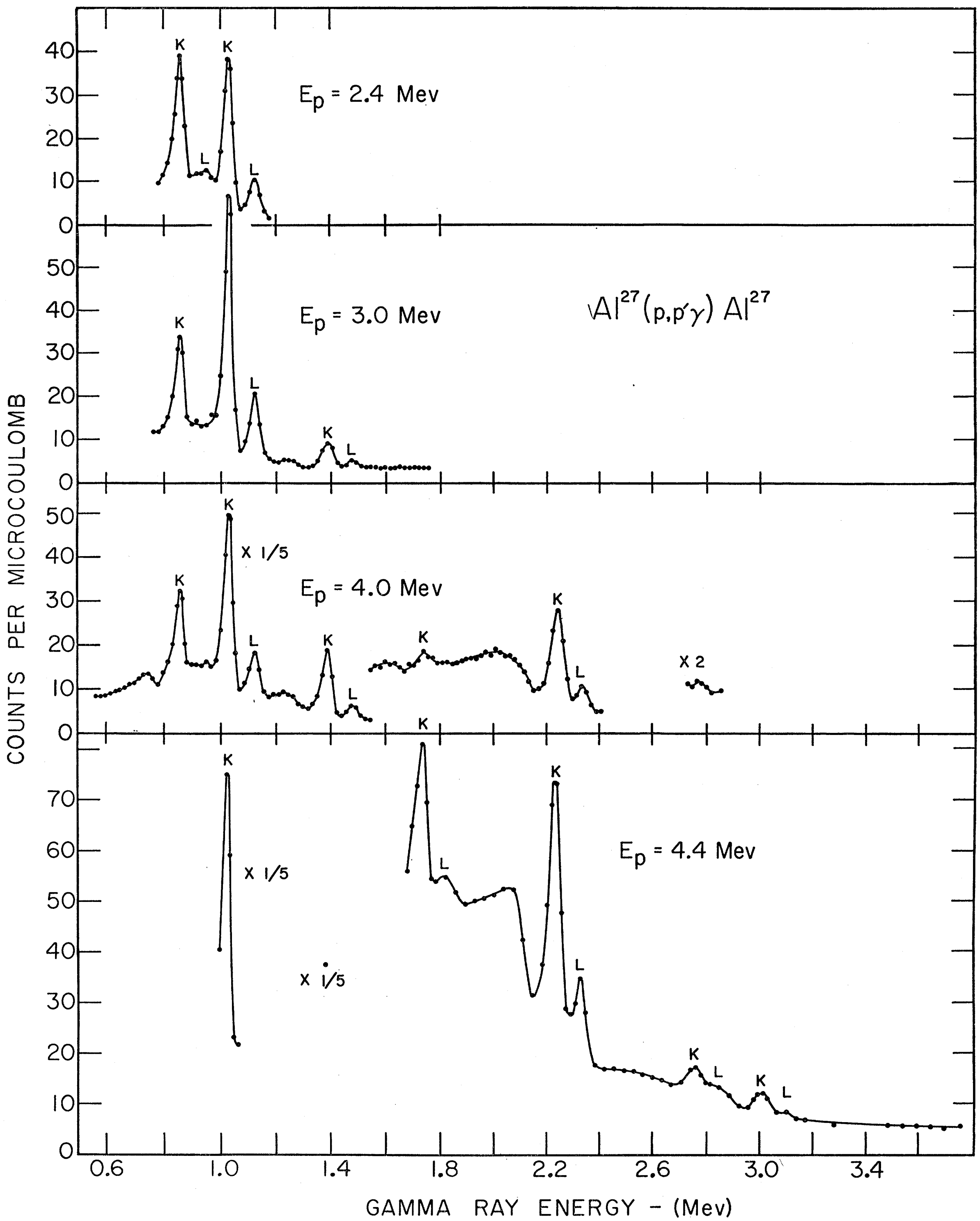

FIG. 1. The γ-ray spectra from $Al^{27}(p,p')$ and $Al^{27}(p,\alpha)Mg^{24}$ obtained at proton energies of 2.4, 3.0, 4.0, and 4.4 Mev.

only slightly poorer than the resolution of 2.4% obtained with 0.976-Mev internal-conversion electrons from a Bi^{207} source.

The γ-ray spectra obtained are shown in Fig. 1 and indicate γ rays with Doppler-corrected energies of 0.845 ± 0.006, 1.014 ± 0.007, 1.369, 1.722 ± 0.010,

TABLE II. Relative intensities of γ rays from $Al^{27}+p$ as a function of the proton energy.

E_p (Mev) \ E_γ (Mev)	0.845	1.014	1.369	1.722	2.216	2.741	2.992
2.4	30	63					
3.0	21	91	6.1				
4.0	100	332	180	~16	131	~7	
4.4		416	272	113	270	30	34

2.216±0.010, 2.741±0.015, and 2.992±0.015 Mev. The energy scale has been adjusted so that the position of the *K*-electron peak represents the γ-ray energies. The observed and Doppler-corrected γ-ray energies are listed in Table I together with the expected energies obtained from the work of Browne *et al.*[7] The relative intensities of the γ rays are given in Table II. All γ-ray energies have been determined relative to the 1.3687±0.00005 Mev γ ray from the $Al^{27}(p,\alpha)Mg^{20}$ reaction. This γ ray is not subject to a Doppler shift[10] and its energy relative to the gammas from Co^{60} has been accurately measured, through the use of a Na^{24} source, with a magnetic lens spectrometer.[11] (The energy quoted has been corrected for a more recent determination of the Co^{60} γ-ray energies.[12]) The calibration of the spectrometer was carried out at a proton bombarding energy of 2.2 Mev to insure that no error could be introduced by the presence of a cascade γ ray from the 2.216- to 0.845-Mev levels of Al^{27}.

For the proton energies used in these experiments the inelastic scattering and (p,α) reactions are the only ones which should yield intense γ radiation. The level schemes for the product nuclei, Al^{27} and Mg^{24}, are shown in Fig. 2. It is clear that the 0.845-, 1.014-, and 2.216-Mev gammas are ground-state transitions from the first, second, and third excited states of Al^{27}, and that the 1.722-Mev gamma is a cascade between the 2.732- and 1.013-Mev levels in Al^{27}. Even for the higher bombarding energies it is probable that the 1.369-Mev gamma is primarily from Mg^{24}. From neutron inelastic scattering results the intensity of the $2.213 \rightarrow 0.843$ Mev cascade relative to the $2.213 \rightarrow 0$ Mev transition in Al^{27} may be variously interpreted to be less than about 0.10 [4,6] or about 0.30.[5] The amount of possible contribution of this cascade to the peak at 1.369 Mev observed in the present experiments cannot be determined directly. However, surveys of the γ-ray spectrum made with a 3-inch×3-inch NaI crystal for proton bombarding energies of 3.58 and 4.45 Mev provide some indication of the amount of cascading. For these measurements the target was a 2.84-mg/cm² Al foil. The γ-ray intensities obtained in this manner are shown in Table III.

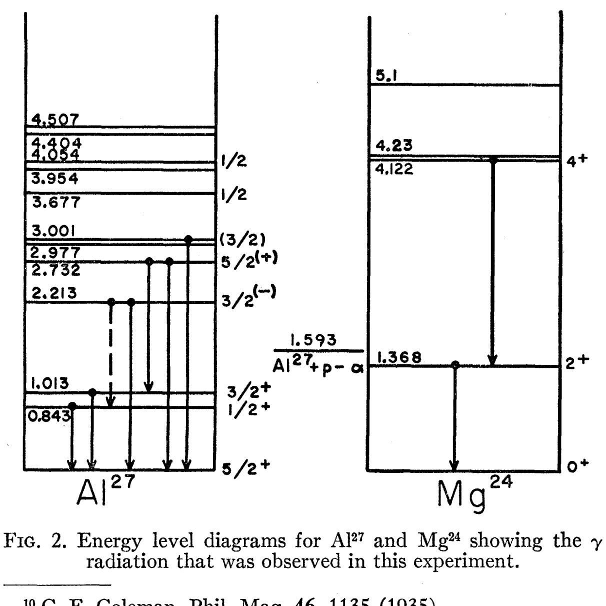

FIG. 2. Energy level diagrams for Al^{27} and Mg^{24} showing the γ radiation that was observed in this experiment.

It may be seen that, while the 0.845-Mev gamma yield is about the same for the two proton energies and the yield of the 1.014-Mev gamma changes only by the amount of the increase of the $2.732 \rightarrow 1.013$-Mev cascade, the yield of the 2.216-Mev radiation increases by a factor of 6.5. Since the target was relatively thick it seems unlikely that the direct population, by inelastic proton groups, of the 0.845-Mev level would decrease much over this energy interval and hence it is probable that the amount of $2.213 \rightarrow 0.843$ cascade is less than 0.15 the intensity of the ground-state transition from the 2.216-Mev level.

TABLE III. Yields of γ radiation from $Al^{27}+p$ for $E_p=3.58$ and 4.45 Mev.

E_γ (Mev)	$10^5\times$(No. of Gamma rays per microcoulomb) $E_p=3.58$ Mev	$E_p=4.45$ Mev
0.845	245	265
1.014	448	530
1.369	101	340
1.722	~6	92
2.216	64	419

The γ-ray peak with an uncorrected energy of 2.749 Mev, which was observed for a proton energy of 4.4 Mev, cannot be definitely assigned since it falls about midway in energy between the expected Doppler-shifted energy of 2.740 Mev for the $2.732 \rightarrow 0$ transition in Al^{27} and the presumably unshifted $4.122 \rightarrow 1.369$ $(E_\gamma = 2.753)$ Mev $E2$ transition in Mg^{24}. The most reasonable interpretation is that the 2.749-Mev peak represents approximately equal contributions from those two γ-ray sources. It is interesting to note that even if this peak is entirely from Al^{27}, the branching ratio of the $2.732 \rightarrow 1.013$ Mev cascade to the ground-state transition is 3.8. Since the ground state of Al^{27} has a spin and parity assignment of $\frac{5}{2}+$ and the 1.014-

[10] C. F. Coleman, Phil. Mag. 46, 1135 (1935).
[11] A. Hedgran and D. Lind, Arkiv Fysik 5, 177 (1952).
[12] Lindström, Hedgran, and Alburger, Phys. Rev. 89, 1303 (1953).

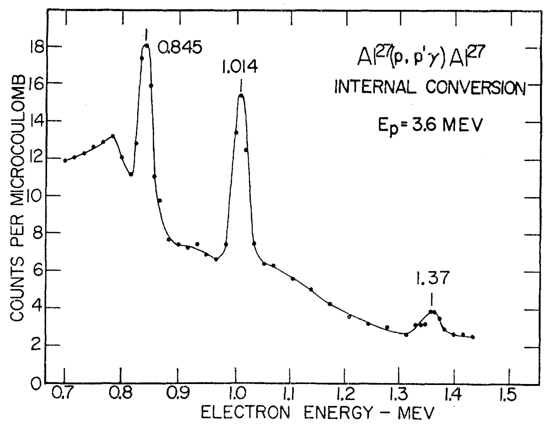

FIG. 3. The internal conversion spectrum from the bombardment of Al^{27} by protons.

Mev state a $\frac{3}{2}+$ assignment,[13,14] the spin value of $\frac{5}{2}$ determined for the 2.732-Mev state by Van der Leun *et al.*[14] requires the same multipolarity for the two γ rays in question. It is apparent that the spin and parity assignments and the observed branching ratio are inconsistent with single-particle-model transition probabilities. A similar situation prevails if the 2.732-Mev state is given any assignment other than $\frac{1}{2}$. But with this spin a strong $2.732 \rightarrow 0.843$ Mev transition would be expected, and the present results indicate that the intensity of such a transition is less than 5% of the intensity of the 1.722-Mev γ ray.

If the parity of the 1.013-Mev level is taken to be odd and that of the 2.732-Mev state to be even, then the presently accepted spin values give single-particle transition probability ratios which agree with the observed ratios. However, the assignment of odd parity to the 1.013-Mev state is consistent neither with the observation that $Mg^{27}(\beta^-)Al^{27}$ transition from the $\frac{1}{2}+$ ground state of Mg^{27} is an allowed transition,[14] nor with internal conversion results which appear in this paper.

Radiation from either the 2.977- or the 3.001-Mev level of Al^{27} has been observed at four different resonances of the $Mg^{26}(p,\gamma)Al^{27}$ reaction.[14] For the resonance at $E_p=0.339$ Mev (7.745-Mev excitation of Al^{27}), either the 2.977- or 3.001-Mev level of Al^{27} is seen to decay by cascade to the 1.013-Mev state ($E_\gamma=1.97$ Mev) with an intensity twice that of the ground-state transition. The angular distribution of the $7.745 \rightarrow$ (2.977 or 3.001) Mev transition indicates a spin of $\frac{3}{2}$ for the cascading state (3.001 or 2.977). At the $E_p=0.454$-Mev resonance the 3.0-Mev γ ray appears to be considerably stronger than the cascade. The present experiment indicates that the cascade from the 2.977- or 3.001-Mev level to the 1.014-Mev state has an intensity of <0.15 times that of the ground-state transition. If the 2.992-Mev radiation observed in this experiment is identified with the $3.001 \rightarrow 0$-Mev transition, then the 2.977-Mev level must be the one with $J=\frac{3}{2}$. Although the limit of error of the observed energy of 2.992 Mev does not definitely preclude the assignment of the radiation to the $2.977 \rightarrow 0$ Mev transition, the fact that the 2.977 or $3.001 \rightarrow 1.013$ Mev cascade was not observed rules out the possibility that the observed peak represents a mixture of ground-state transitions from both of these states.

B. Internal Conversion Spectra

Although the internal conversion coefficients for low-Z nuclei and for γ-ray energies in the range of 1 to 2 Mev are of the order of 10^{-5}, it was thought that the lead shielding of the magnetic lens spectrometer and also the use of a small scintillating element might result in a sufficiently low background to make possible detection of internal-conversion electrons associated with the intense low-energy γ rays from $Al^{27}+p$. Accordingly a 2.84-mg/cm² aluminum target was mounted without a radiator and bombarded with 3.58- and 4.45-Mev protons. The resulting internal conversion spectrum for 3.50-Mev protons is shown in Fig. 3. For the higher energy γ rays, just enough points were taken to determine the peak height relative to background and these are not shown in Fig. 3. The 0.845-, 1.014-, and 1.369-Mev internal conversion peaks are quite prominent, but the higher energy lines are barely distinguishable from background. The internal electron yields were determined relative to the number of 0.972-Mev electrons from a calibrated Bi^{207} source.

As mentioned previously, a 3-inch×3-inch NaI crystal was used to measure the yield of γ radiation when the same Al^{27} target was bombarded with protons of the energies used in the electron yield determinations. The measured and theoretical internal conversion coefficients are listed in Table IV. The theoretical values for the K shell have been interpolated from curves calculated by Rose *et al.*[15] These have been corrected for L-shell contributions through the use of K/L ratios obtained for $Z=15$.[16] In computing these coefficients consideration must be given to the angular

TABLE IV. Experimental and theoretical internal conversion coefficients for $Al^{27}+p$.

E_γ (Mev)	Internal conversion coefficients $\times10^5$ Experimental	Theoretical α_1	β_1	α_2	β_2	Assignment
0.845	3.9 ±0.9	1.7	2.6	4.6	6.2	$E2$
1.014	1.8 ±0.4	1.2	1.8	2.8	3.6	$M1$
1.369	1.3 ±0.3	0.59	1.1	1.4	2.0	$E2(+M1)$
1.722	0.73±0.40	0.49	0.75	0.88	1.3	($M1$, $E1$, $E2$)
2.216	0.36±0.14	0.33	0.50	0.57	0.77	($E1$, $M1$)

[13] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 700 (1957).

[14] Van der Leun, Endt, Kluyver, and Vrenken, Physica **22**, 1723 (1956).

[15] M. E. Rose (unpublished).

[16] M. E. Rose, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Appendix IV.

distribution of the γ radiation and of the internal conversion electrons. Theoretical expressions have been derived by Rose *et al.*[17] for the angular distribution of internal conversion electrons relative to the angular distribution of the associated γ ray and from these expressions estimates can be made of the correction necessitated by angular distribution effects. In the present experiments the γ-ray yields were measured at 0°, 45°, and 90° and all the γ rays observed were found to be isotropic to within less than 10%. On the basis of these results complete isotropy of gammas and electrons was assumed and no correction was made.

The values obtained for the internal conversion coefficients appear to provide excellent confirmation of the assignments of $\frac{1}{2}^+$ and $\frac{3}{2}^+$ for the spin and parity of the 0.845- and 1.014-Mev states in Al^{27}. A multipolarity of either $M1$ or $E2$ is consistent with the coefficient for the 1.369-Mev γ ray. As mentioned previously, this γ ray is known to be an $E2$ transition with the possibility of a small admixture of $M1$. The results for the 1.722-Mev γ ray favor $M1$ but cannot exclude $E1$ or $E2$. The fact that this gamma is a strong cascade from the $J=\frac{5}{2}^{(+)}$, 2.732-Mev state to the 1.014-Mev $\frac{3}{2}^+$ state favors $E1$ or $M1$ over $E2$. While the present data do not completely exclude an $M1$ multipolarity for the 2.216-Mev transition, an $E1$ assignment is favored. For these favored multipolarities to be consistent with the J values obtained by Van der Leun *et al.*,[14] the spin and parity of the 2.216- and 2.732-Mev states must be $\frac{3}{2}^{(-)}$ and $\frac{5}{2}^{(+)}$, respectively.

$F^{19}+p$

The γ rays obtained from the $F^{19}(p,p'\gamma)F^{19}$ reaction have been carefully studied by Toppel *et al.*,[18] who used scintillation and coincidence counting techniques. In the present work the photoelectron spectra for this reaction were observed with the magnetic lens spectrometer for proton bombarding energies of 3.22, 3.65, and 4.27 Mev.

TABLE V. Relative intensities of γ rays from $F^{19}(p,p'\gamma)F^{19}$.

E_γ (Mev)	$E_p=3.22$ Mev	$E_p=3.65$ Mev	$E_p=4.27$ Mev
1.236	30	17	16
1.358	44	83	100
1.46	<4	~ 9	<3

The observation of photoelectrons from low-energy inelastic-scattering γ rays is rendered difficult by the presence of nuclear pairs from the $F^{19}(p,\alpha\pi)O^{16}$ reaction. The cross section for production of nuclear pairs is much lower than that for inelastic scattering, but only about one in 10^3 gammas is photoconverted by the thin radiator required for good spectrometer resolution. In order to minimize the number of nuclear pairs, the proton bombarding energies were chosen at low-yield points in the $F^{19}(p,\alpha\pi)O^{16}$ excitation curve.[19] The γ-ray spectra were obtained by bombarding a 2.2-mg/cm² thick CaF_2 target evaporated onto a 16.3-mg/cm² Th foil. A correction for pair background has been made which amounts to as much as 80% of the uncorrected counting rate for the peak at 1.35 Mev.

The energies of the γ rays which were observed in the energy range studied are 1.236±0.010, 1.358±0.10, and 1.46±0.030 Mev. These energies are not corrected for a maximum Doppler shift of 5 kev. The last energy is less accurate than the other two because the presence of this γ ray was detected by the low value of the K/L peak ratio of the 1.358-Mev gamma at the 3.65-Mev bombarding energy. The identification of these γ rays with the energy levels[20] of F^{19} has been made by Toppel *et al.*[18] The 1.236-Mev γ ray is a cascade from the 1.350- to the 0.112-Mev state of F^{19}. The 1.358-Mev peak is primarily from the 1.462- to 0.112-Mev and 1.558- to 0.197-Mev cascades while the 1.462-Mev gamma is a ground-state transition from the 1.462-Mev level. The intensities of these γ rays for the three bombarding energies are given in Table V. The values quoted are relative to the value of 100 for the 1.36-Mev gamma peak at $E_p=4.27$ Mev.

[17] Rose, Biedenharn, and Arfken, Phys. Rev. **85**, 5 (1952).
[18] Toppel, Wilkinson, and Alburger, Phys. Rev. **101**, 1485 (1956).
[19] Ranken, Bonner, and McCrary, Phys. Rev. **109**, 1646 (1958).
[20] Squires, Bockelman, and Buechner, Phys. Rev. **104**, 413 (1956).