FEBRUARY 1, 1940 PHYSICAL REVIEW VOLUME 57

Gamma-Rays from Aluminum Due to Proton Bombardment

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(Received November 16, 1939)

A study has been made of the excitation of gamma-rays from thin films of aluminum bombarded by protons in the energy region 0.46 Mev to 2.6 Mev. The excitation curve exhibits a complex system of closely spaced resonances over the entire region investigated. By means of coincidence counters measurements were made of the average energy of the radiation emitted at several of the resonances.

Introduction

A PRELIMINARY investigation of the yield of gamma-rays from thick targets of aluminum bombarded by protons was made at this laboratory three years ago by Herb, Kerst and McKibben.[1] In this work the yield was investigated up to 2.1 Mev. More recently Gentner[2] made a study of this reaction using protons in the low voltage region on a thick aluminum target. The gamma-ray yield curves obtained at this laboratory and by Gentner showed a number of steps indicating resonance excitation and suggested that a detailed investigation of the yield from a thin aluminum film might be profitable.

In the present work gamma-ray yields from two thin films of aluminum were investigated in detail up to 2.6 Mev. By means of the coincidence counter method for determining gamma-ray energies measurements were made of the average energy of gamma-rays from several of the resonance levels.

Excitation Curves

Relative gamma-ray intensities were measured with a Lauritsen type electroscope arranged as in the previous work on gamma-rays from fluorine[3] and a current integrator previously described[1] was used for measuring total charge incident on the target.

For a preliminary survey of the low voltage region a thick-target yield curve was obtained as shown by curve *A*, Fig. 1. A thick target excitation curve such as this does not serve to give details of resonance structure but it does help for locating resonances in the low voltage region. Searching for these resonances from a thin film is very time-consuming since resonances may be missed unless yields are taken at closely spaced voltages over the entire region.

Aluminum films for the thin-film work were prepared by evaporating aluminum on to tantalum sheets. Tantalum was found to give no observable gamma-ray yield when bombarded by protons at the maximum generator voltage.

Film 1

Film 1, used for curve *B* of Fig. 1 was prepared from Alcoa aluminum with a specified purity of 99 percent. Because of the complexity of the resonance system and the multiplet structure, voltage settings were taken as closely together as was practicable with normal generator performance. Convenient voltage intervals were determined by the galvanometer scale of the generating voltmeter. For most of the work voltage settings were made at intervals of one millimeter, which corresponded to voltage intervals of about 6 kev. To establish the positions of the aluminum resonances accurately the position of the resonance peak at 1.368 Mev was checked against the 0.862-Mev fluorine resonance. A CaF_2 crystal covered with nickel gauze was used for this voltage calibration. After several determinations had fixed the position of the 1.368-Mev resonance it was then used as a standard check in all of the aluminum work.

During the course of the work on the excitation curves some difficulty was experienced because of changes in the sensitivity of the voltmeter galvanometer. To minimize the possibility of

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[1] R. G. Herb, D. W. Kerst and J. L. McKibben, Phys. Rev. **51**, 691 (1937).

[2] W. Gentner, Zeits. f. Physik **107**, 354 (1937).

[3] E. J. Bernet, R. G. Herb and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).

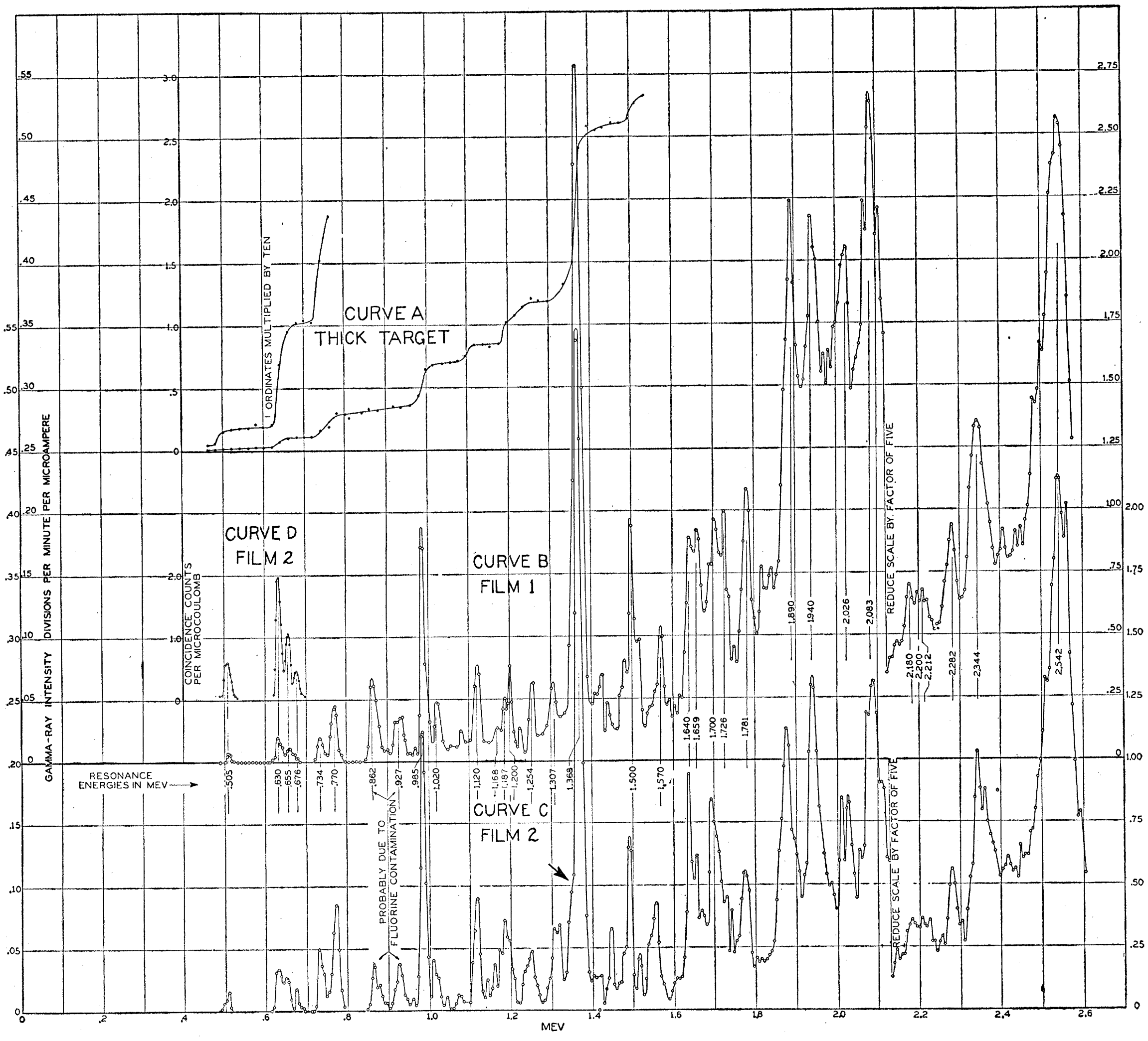

FIG. 1. Gamma-ray intensity from thin and thick aluminum targets *vs.* energy of bombarding protons. Resonance energies (not corrected for film thickness) are given for the resonances which are believed to be fairly well established.

error in voltage measurements the voltage calibration was checked frequently by taking a yield curve over the 1.368-Mev peak.

In the lower voltage region of the excitation curve, which was taken first, background intensity was relatively low, but it rose rapidly when the yield curve was carried above 1.4 Mev. An investigation showed that part of the background was caused by protons striking the brass of the magnetic analyzer, but that most of the radiation came from a quartz ring in front of the defining aperture of the target chamber. Rough yield curves from a target of quartz and from a target of pure silicon showed that the radiation was due chiefly to silicon. The gamma-ray intensity from silicon was found to rise rapidly with voltage, but a detailed yield curve was not obtained and no conclusions could be drawn concerning possible resonance structure.

When a target is bombarded over a prolonged period a carbon deposit forms and it appeared possible that this deposit might be responsible for some of the gamma-radiation observed from the aluminum targets. Before further work was done on the yield curve from aluminum, gamma-ray yields from a thick target of carbon were measured at 61-kev intervals up to 2.1 Mev. From 0.55 Mev to 1.4 Mev the yield showed no appreciable rise. A smooth rise between 1.4 Mev and 1.9 Mev indicates the existence of a broad, weak resonance in this region.

No further measurements were made on carbon since there appeared to be little possibility that a thin carbon film could be responsible for any of the resonance peaks observed from the aluminum targets.

After elimination of the background radiation from brass and from quartz the aluminum yield curve was carried from 1.4 Mev up to 2.6 Mev. The background yield was found to increase with voltage but at every voltage at which it was measured its intensity was less than $\frac{1}{10}$ of the intensity from the aluminum film at that voltage. In all of the work on aluminum, electroscope readings were corrected for natural drift but no correction was made for background intensity.

Film 2

As a check on the accuracy of the yield curve obtained from film 1, a second thin target of approximately the same thickness (film 2) was prepared by evaporation of highly purified aluminum[4] onto a tantalum sheet. Curve *C*, Fig. 1, was obtained using this film. As in the previous work on film 1 the voltmeter was calibrated frequently by going over the 1.368-Mev peak. The ratio of background intensity to the intensity from aluminum was approximately the same as in the work on film 1.

During the course of this work apparatus was developed for coincidence counting. This apparatus proved more suitable than the electroscope for the detection of weak radiation, and was used to obtain a yield curve in the voltage region below 0.700 Mev (Curve *D*, Fig. 1). It is probably that the coincidence counter method would have given better results than the electroscope over the entire yield curve but because of lack of time no further work was done.

The positions of the resonances observed in the low voltage region do not agree with the results of Gentner who obtained gamma-ray resonances at 425 kev and 560 kev from a thick target of aluminum. In taking the data for curve *B* of Fig. 1, the low voltage region was investigated after prolonged bombardment of the film and it was thought possible that the resonance voltages were shifted because of a carbon deposit. However, for curves *C* and *D* clean aluminum was used for investigation of the low voltage region and carbon deposits could not be responsible for an appreciable shift in the positions of resonances. Since the voltmeter was checked during the work on the low voltage region it seems unlikely that the positions given for these resonance peaks could be greatly in error.

Yields from thick aluminum were measured roughly down to 0.325 Mev where gamma-radiation still appeared to be observable, but sufficient time was not spent on this work to obtain a reliable excitation curve.

Widths of Resonance Levels

The experimental widths of resonance peaks are due partially to the thickness of the aluminum films. Estimates of the contribution of film thickness were made in the following way. The area under a thin target peak was divided by the height of the corresponding thick target step. The quotient gives the absorption thickness of the aluminum film and is independent of the homogeneity of the proton beam and of voltage fluctuations providing they remain the same during the measurements.

The resonance peaks at 0.985 Mev and 1.368 Mev were used for estimating film thickness. The values obtained were not very consistent but they indicate that the absorption thicknesses of films 1 and 2 were nearly equal with a value of approximately 10.5 kev for protons having an energy of 0.985 Mev.

For the data taken with film 1 below 0.960 Mev the target was turned at an angle of 59° from perpendicularity with the proton beam so that its effective thickness was increased by a factor of 1.93 and the values for gamma-ray intensities were divided by 1.93 before plotting. This method of treating the data probably caused the difference in this region between relative heights of peaks from film 1 and the corresponding peaks from film 2.

Peaks in this region are not as wide as should be expected from the original measurements on film thickness. It is believed that this was caused

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[4] This aluminum was obtained through the courtesy of Dr. F. C. Frary, Aluminum Research Laboratory, Aluminum Company of America. It had a specified purity of 99.97 percent.

by evaporation of aluminum from the target, since during this work the bombardment current used was much higher than that used in other voltage regions. For proton energies above 1.4 Mev on film 1, the target was moved so that the proton beam struck a new spot. The target was set at an angle so that its effective thickness was increased by a factor of 1.56 and yield values were divided by 1.56 for plotting. Bombardment current was kept low during this work to avoid evaporation and checks of film thickness from yield measurements at the 1.368-Mev peak showed that evaporation was negligible. Thus the effective thickness of film 1 in this region was approximately 1.5 times the thickness of the film used for curve *C*, which was always set perpendicular to the proton beam. This difference in film thickness may explain why the intensities in the upper voltage region of curve *B* do not drop as low between resonance peaks as the corresponding intensities for curve *C*.

The relative intensities of the peaks of curve *C* are probably fairly reliable since bombarding currents were kept low and checks on the intensity of the 1.368-Mev peak showed that evaporation was negligible. One spot on the film was used for the entire excitation curve. For the data of curve *D* the target was shifted so that the proton beam struck a spot not previously bombarded.

The half-widths of 9 resonances corrected for film thickness are given in Table I. Curve *D* was used for determining experimental half-widths of the resonances it includes and curve *C* was used for determining experimental half-widths of the other resonances listed in Table I. Resonances below 1.368 Mev which are not included in Table I were not obtained with sufficient accuracy of detail to provide reliable values for half-widths. With the exception of the 1.120 Mev and 1.368 Mev resonances experimental half-widths appear to be due principally to film thickness. Unless the values determined for film thickness are greatly in error, these resonance levels must be very sharp.

TABLE I. *Half-widths of resonance peaks with corrections for film thicknesses. Corrected half-widths are estimated to be accurate to 4 kev.*

RESONANCE ENERGY (MEV)	MEASURED HALF-WIDTHS (KEV)	FILM THICKNESS (KEV)	CORRECTED HALF-WIDTHS (KEV)
0.505	18.6	17.3	1.5
0.630	15.4	14.6	0.8
0.655	15.4	14.2	1.2
0.676	15.4	13.8	1.6
0.734	17.0	13.0	4.0
0.770	17.0	12.6	4.4
0.985	12.4	10.5	1.9
1.120	17.0	9.7	7.3
1.368	18.6	8.8	9.8

Above the 1.368-Mev peak the resonance structure appears to be very complex. Some of the small satellites may have been caused by changes in background intensity, but many are believed to be genuine. Individual components of many of the resonance peaks are very sharp, but half-value widths have not been estimated since details of the curves are not established with sufficient accuracy. The relative heights of the individual components shown in curve 1 differ considerably from those shown in curve 2. These differences may be due, at least partially, to the difference in the thicknesses of film 1 and film 2. Errors in reading the electroscope and difficulties with voltage fluctuations may also account for much of the difference. In some instances a change of voltage of $\frac{1}{10}$ percent could change intensity sufficiently to make a well-resolved satellite appear only as a shoulder.

POSSIBILITY OF FLUORINE CONTAMINATION

In the previous work on gamma-radiation from thin films of fluorine, prominent resonance levels were found at 0.862 Mev, 0.927 Mev, and at 1.363 Mev. The heights of the peaks at 0.862 Mev and at 0.927 Mev were 9/10 and 5/10, respectively, of the height of the 1.363-Mev peak. The yield curves from aluminum show a prominent resonance at 1.368 Mev and weak resonances at approximately 0.862 and 0.927 Mev. The gamma-radiation from fluorine is much more intense than that from aluminum and the close correspondence in the above resonance voltages strongly suggests the presence of fluorine as a contaminant in the aluminum. There seems to be no possibility that the intense 1.368-Mev resonance obtained from the aluminum targets could be due to fluorine contamination. In all the work on aluminum the intensity of this peak relative to other intensities from aluminum remained the same.

If this peak were due to fluorine contamination, then fluorine radiation in other voltage regions should appear in the proper proportions. Except at 0.863 Mev and 0.927 Mev no similarity could be observed in the form of the yield curves from fluorine and aluminum. Furthermore, the resonance peaks observed from aluminum at 0.863 Mev and 0.927 Mev are only $\frac{1}{6}$ to $\frac{1}{10}$ as intense as should be expected, if the 1.368-Mev peak is due to fluorine. Thus fluorine contamination cannot be responsible for an appreciable fraction of the intensity observed from aluminum at 1.368 Mev, but the radiation at 0.862 Mev and at 0.927 Mev is probably due, at least in part, to fluorine. The form of the thick-target yield curve in this region shows that if an aluminum resonance is present it must be very weak. The commercial aluminum used for film 1 and the highly purified aluminum used for film 2 both had specified fluorine contents too low to contribute an observable intensity in any region of the yield curve, and it therefore seems probable that during the process of preparation of the thin films some fluorine contamination was introduced.

The fluorine contamination on film 1 appears to have been greater than that on film 2. From a consideration of the relative heights of these peaks as they appear in curves *B* and *C*, and the relative voltage positions of their maxima, it seems probable that there is a weak aluminum resonance near the 0.927-Mev fluorine resonance.

The close correspondence in the voltage positions of the 1.363-Mev fluorine resonance and the 1.368-Mev aluminum resonance suggests that this radiation might be due to a common contaminant, yet a consideration of all yield curves from aluminum and fluorine during the last three years contradicts this assumption. In thick-target yield curves from CaF_2 crystals and thin-target yield curves from tantalum fluoride films, the 1.363-Mev resonance always appeared in the same proportion with respect to other fluorine resonances. Similarly for thin and thick targets prepared from aluminum of different degrees of purity the 1.368-Mev resonance always appeared in the same proportion with respect to other aluminum resonances.

Two curves taken over the 1.368-Mev aluminum resonance showed a small satellite at the position indicated by an arrow on curve *C*. The fluorine 1.363 Mev resonance was definitely shown to have a satellite similarly located. Results on the satellite of the aluminum resonance are as yet inconclusive. If present, it is not as prominent as that on the fluorine resonance. No explanation has been found for the striking correspondence in voltage position, relative prominence, and shape between the 1.368-Mev aluminum resonance and the 1.363-Mev fluorine resonance. It is assumed therefore that the correspondence is accidental.

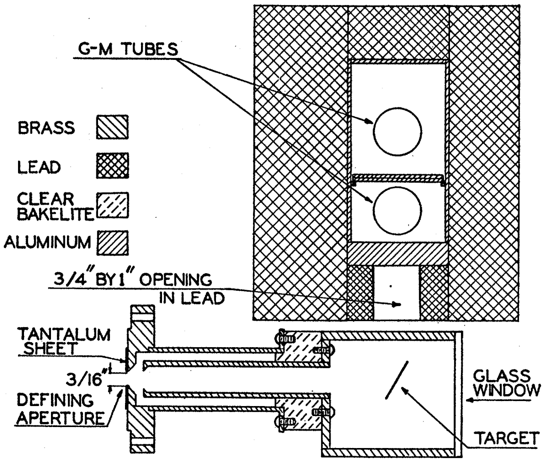

FIG. 2. Apparatus used for measurement of gamma-ray energies.

GAMMA-RAY ENERGIES

The reaction responsible for the emission of gamma-radiation from aluminum is one of radiative capture. In this reaction,

$$Al^{27}+H^1\rightarrow Si^{28}+h\nu,$$

the energy release is 10.6 Mev plus the energy of the bombarding proton.

Gentner investigated the energies of the gamma-rays emitted from a thick target of aluminum bombarded by protons of 0.600 Mev. He used two Geiger-Müller tubes operating in coincidence for detecting secondary electrons ejected from aluminum and determined the thickness of aluminum absorber which reduced the coincidence yield to one-half its value with no absorber between the counting tubes.

From this measured half-value thickness and a calibration curve relating half-value thickness to

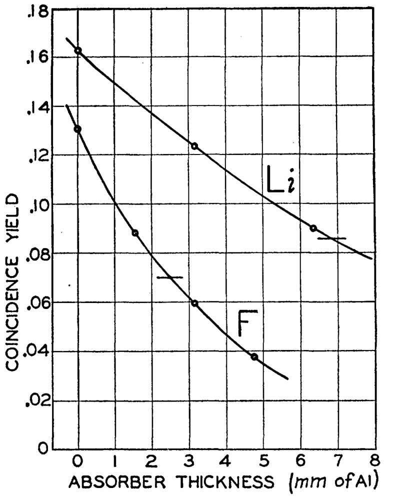

Fig. 3. Absorption curves for secondary electrons due to gamma-rays from lithium and from fluorine.

gamma-ray energy, Gentner concluded that the average energy of the gamma-rays he observed from aluminum was 3.4 Mev.

It was thought probable that gamma-radiation emitted in this reaction might vary from level to level over the yield curve and that an investigation of the radiation emitted at different resonances might give information regarding the energy level system of Si^{28}. In carrying out this investigation the coincidence method was used and following Gentner and other workers the half-value thickness of absorber was used in conjunction with a calibration curve for estimating average gamma-ray energies.

The Geiger-Müller tubes used for this work have glass envelopes with thin portions 0.10 to 0.20 mm thick, 5 cm long and 2 cm in diameter. A thin silver coating inside the tube served as the cathode. After the tubes were outgassed by a hydrogen discharge, they were filled with hydrogen to a pressure of 7 cm of Hg.

The counter tubes were mounted inside a lead box as shown in Fig. 2. Gamma-rays from the target enter the lead box through a rectangular opening 1″×$\frac{3}{4}$″. An aluminum plate $\frac{3}{8}$″ thick was placed as shown in Fig. 2, to provide a source of secondary electrons. It covered the entire lead floor of the box as well as the aperture and therefore served to absorb secondary electrons generated in the lead.

The Neher-Harper method of quenching the discharges was used, with a 2-megohm resistor and a 6J7 tube. Circuit constants are those of Wilson[5] except that an adjustable positive grid bias was added to the second stage to improve resolving time. An arrangement also was made by which single counts in the lower of the counting tubes were recorded as well as the coincidence counts, and coincidence yield was taken as the ratio of coincidence counts to single counts. This procedure was helpful in thin-film work where a small change in voltage could cause a large change in gamma-ray yield.

Scaling circuits were used both for counting pulses from the lower tube and for counting coincidences. Measurements of the resolving time of the circuit as used, gave values of 4×10^{-5} to 6×10^{-5} second.

Absorption Curves

Gamma-rays from protons on lithium and from protons on fluorine were used for obtaining a calibration curve giving half-value thickness as a function of gamma-ray energy. During the course of the work from June 12 to August 12, six absorption curves were taken for the secondary electrons due to gamma-rays from fluorine, in which the half-value thicknesses ranged from 2.7 to 2.9 mm of aluminum. All the data on fluorine were averaged to give the curve shown in Fig. 3. Absorption curves for the secondary electrons from lithium gamma-rays were taken

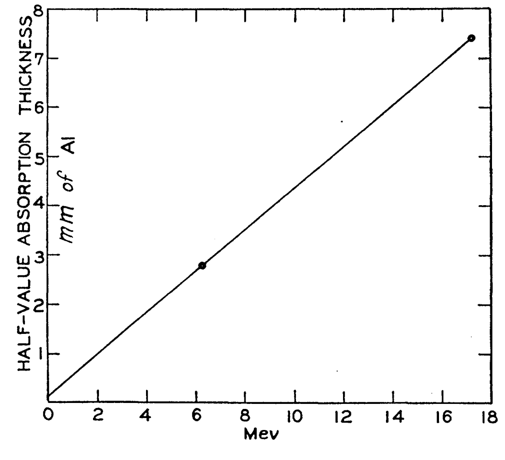

Fig. 4. Showing half-value absorption thickness as a function of gamma-ray energy.

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[5] V. C. Wilson, Phys. Rev. **53**, 337 (1938).

on June 15 and August 12, and half-values of 7.2 and 7.4 mm, respectively, were obtained. Yields were averaged to give the curve for lithium shown in Fig. 3.

Measurements of the effective counter wall thickness by coincidence counting and by rough optical methods gave values between 0.10 and 0.20 mm of aluminum. Each absorption curve was therefore extrapolated back 0.30 mm to give the coincidence yield that would result if there were no counter walls acting as an absorber, and the thickness of aluminum which reduced the yield to half that value was found from the curve.

The half-value thicknesses determined by the curves of Fig. 3 give the values which are plotted in Fig. 4, showing gamma-ray energy as a function of half-value absorption thickness.

Results from aluminum were averaged to give the curves shown in Fig. 5. Since the coincidence yields for zero thickness of absorber varied slightly, yields were adjusted to make these points coincide. For this adjustment, the ordinates of curves *F*, *G*, and *H* were multiplied by 0.998, 0.996 and 1.042, respectively. For curves *F*, *G*, and *H* two thousand or more coincidences were counted at each point. For curve *E*, 980 counts were obtained at the lowest point and over two thousand at the other two.

Gamma-ray energies determined by the curves of Fig. 5 are given in Table II.

The values determined for gamma-ray energies are much lower than should be obtained if the energy is released in only one step and they are considerably too high for agreement if a two-step radiative process is assumed. Moreover the rise in observed values of gamma-ray energies in going from low voltage to high voltage resonances is considerably greater than expected from a one-step or a two-step radiative process.

TABLE II. *Energies of gamma-rays from aluminum as determined by curves of Fig. 5. The value 11.2 Mev for the available energy due to 700-kev protons on a thick target is a rough average for the resonances which are excited.*

CURVE	PROTON ENERGY (MEV)	TARGET	HALF-VALUE (MM OF AL)	GAMMA-RAY ENERGY (MEV)	REACTION ENERGY AVAILABLE (MEV)
E	0.550	Thick	2.70	6.1	11.1
F	0.700	Thick	2.87	6.5	11.2
G	0.985	Thin	3.40	7.7	11.6
H	1.368	Thin	3.60	8.2	12.0

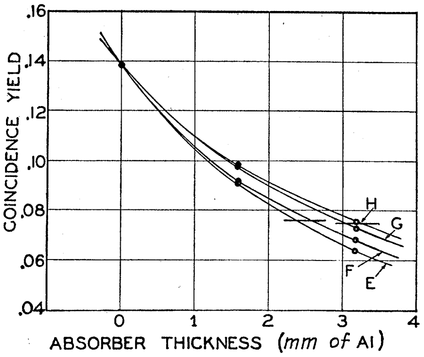

FIG. 5. Absorption curves for secondary electrons due to gamma-rays from aluminum. Curve E, 0.550-Mev protons on thick aluminum target. Curve F, 0.700-Mev protons on thick aluminum target. Curve G, 0.985-Mev protons on thin aluminum target. Curve H, 1.368-Mev protons on thin aluminum target.

The experimental results can be explained if it is assumed that a certain percentage *P* of the nuclei radiate in one step and that the remainder radiate in two or more steps. To account for the change in gamma-ray energy with the voltage of resonance, it must be assumed that *P* increases in going from low voltage resonances to high voltage resonances. Values of *P* were computed from the data of Table II assuming that there are no transitions of more than two steps and that the experimental values for gamma-ray energies give the average energies of the radiation. With these assumptions *P* has a value of 18 percent for radiation from the 0.505-Mev level and it rises to 54 percent for radiation from the 1.368-Mev resonance.

A search was made for soft radiation of the order of 1 Mev or less from aluminum bombarded by protons. None was detected, but the results were not conclusive. Background radiation caused difficulty in measurements on weak resonances from thin films. Measurements with a thick target indicated that for protons of energies up to 1.8 Mev, not more than 0.1 of the radiation is soft.

This work was supported by the Wisconsin Alumni Research Foundation, and by a grant from the Penrose Fund of the American Philosophical Society.