A Search for the Transmutation Products of Gamma-Meson Reactions Induced by 100-Mev X-Rays

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Irradiation with 100 Mev x-rays has been found to produce Zn^{63} from copper and Mg^{27} from aluminum. Experiments involving variations in beam energy and target thickness have shown that these isotopes result from secondary reactions caused by photo-neutrons and photo-protons from the target materials rather than from any primary, x-ray induced processes. No evidence for gamma-meson reactions has been obtained. A search for the transmutation products of gamma-meson reactions is shown to compare favorably in sensitivity with cloud-chamber methods for the detection of meson production, provided mesons are produced singly.

I. INTRODUCTION

IF mesons have masses of less than 195 electron masses, it is energetically possible for mesons to be ejected when nuclei are bombarded with 100-Mev x-rays. Schein, Hartzler, and Klaiber[1] have published cloud-chamber photographs of ionizing particles generated by x-rays from the 100-Mev betatron[2] and have interpreted some of their tracks as possibly being meson tracks.

If a charged meson is ejected from a nucleus after excitation with x-rays or gamma-rays, the resulting nucleus will differ from the original nucleus by one unit in charge, but will have the same mass number. Thus it should be possible to detect such a gamma-meson reaction by means of the radioactivity of the product formed if the target isotope is chosen such that its neighboring isobars are known radioactive species. Baldwin and Klaiber[3] bombarded a number of elements with the x-rays from the 100-Mev betatron at Schenectady; among the reactions observed were the production of a 10-minute magnesium period (probably Mg^{27}) from Al^{27} and a 2.6-hour activity (probably Si^{31}) from P^{31}. Baldwin and Klaiber attribute the formation of Mg^{27} from Al^{27} to the action of quanta rather than stray neutrons and suggest as possible mechanisms positron emission, electron capture, or positive meson emission. The reported production of Si^{31} from P^{31} presumably is an analogous case, although the possibility of an (n,p) reaction was not excluded.

In view of these results it seemed worth while to make a more thorough search for the products of hypothetical gamma-meson reactions[4] in betatron bombardments and, in particular, to develop techniques which would enable one to differentiate between gamma-meson reactions, and other possible reactions leading to the same products.

Target materials for these investigations had to be chosen in such a way that gamma-meson reactions would lead to products of convenient half-lives which could be readily identified chemically. In the case of (γ,μ^+) reactions it was also necessary to use a target element having a single isotope, or one whose heaviest isotope gives rise to the activity of interest by (γ,μ^+) reaction, since (γ,μ^+) reaction on a lighter isotope could not be distinguished radiochemically from a (γ,p), (γ,pn) or similar reaction on a heavier isotope. In case of (γ,μ^-) reactions, no such restriction exists.

II. EXPERIMENTAL PROCEDURE

1. General

The two hypothetical gamma-meson reactions[5] chosen for investigation were $Cu^{63}(\gamma,\mu^-)Zn^{63}$ and $Al^{27}(\gamma,\mu^+)Mg^{27}$.

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[1] M. Schein, A. J. Hartzler, and G. S. Klaiber, Phys. Rev. **70**, 435 (1946).

[2] W. F. Westendorp and E. E. Charlton, J. App. Phys. **16**, 581 (1945).

[3] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **70**, 259 (1946).

[4] These will be referred to as (γ,μ^+) and (γ,μ^-) reactions, respectively.

[5] A preliminary report of the work on the first of these reactions was presented at the New York meeting of the American Physical Society on Sept. 19, 1946. cf. G. Freidlander, M. Perlman, and L. Pepkowitz, Phys. Rev. **70**, 790 (1946).

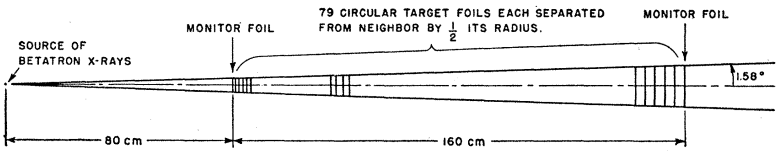

FIG. 1. Schematic diagram of the geometrical arrangement for the bombardment of a thin-foil array.

Briefly, the experiments consisted of exposing the target in the center of the betatron x-ray beam, carrying out rapid chemical separations of the product elements of interest, and following the decay of the samples thus obtained in a standard geometry on a Geiger-Müller counter.

The x-ray intensity in the betatron beam falls off from the central maximum approximately like a Gaussian function;[6] half the total intensity of the 100-Mev beam is contained in a cone of half-angle 2.0 degrees.[2] All the targets used subtended a cone of about 1.6-degree half-angle in the center of the beam, intercepting about 35 percent of the beam.

It proved necessary to use rather thick targets in order to obtain sufficiently active samples for counting. About 2 g/cm^2 of copper and about 0.6 g/cm^2 of aluminum were used. The use of such thick targets introduced the following serious difficulty in interpreting the results: Secondary (p,n) or (n,p) reactions caused by protons or neutrons produced in the thick targets, would give rise to the same products as (γ,μ^-) or (γ,μ^+) reactions, respectively. Assuming an average (p,n) cross section of 10^{-24} cm^2, and a proton range in copper of 0.1 g/cm^2 for the protons produced in copper, one calculates $10^{-24}\times 0.1\times 6\times 10^{23}/63=10^{-3}$ (p,n) processes per proton produced. The number of secondary (n,p) processes per neutron produced in aluminum may be even somewhat higher. Since the observed yields of Zn^{63} from copper and of Mg^{27} from aluminum bombardments were of the order of 10^{-3} to 10^{-4} times the yields of observed (γ,n) and (γ,p) processes, it was clear that additional experiments were necessary to differentiate a (γ,μ^-) from a (p,n) reaction, and a (γ,μ^+) from an (n,p) reaction.

Two types of experiments were devised for this purpose. The first was to vary the bombarding energy. Gamma-meson reactions become energetically impossible for bombarding energies lower than the energy necessary to create the meson mass. If the meson mass is near 200 electron masses, this threshold cannot be much below 100 Mev (if, indeed, it is not greater). Bombardments of copper as well as aluminum were therefore carried out not only at 100 Mev, but also at 50 Mev maximum x-ray energy. In these experiments, the targets were disks 4.4 cm in diameter mounted in a cylindrical textolite pillbox with thin Cellophane windows at both ends. The box was clamped in a Bakelite holder located between the magnet coils of the betatron 80 cm from the x-ray source in the doughnut.

In order to be able to compare the results of the various experiments carried out at different energies, and to determine whether the yields of Zn^{63} and Mg^{27} could be correlated with the production by the x-rays of protons and neutrons in the targets, the beam was monitored in each bombardment by observing the amount of (γ,n) reaction induced in a monitor foil. If the observed formation of Zn^{63} from copper and of Mg^{27} from aluminum resulted from the secondary reactions $Cu^{63}(p,n)Zn^{63}$ and $Al^{27}(n,p)Mg^{27}$, then the yields of these two products should vary with bombarding energy in about the same way as the monitor yields. The reactions $Zn^{64}(\gamma,n)Zn^{63}$ and $Cu^{63}(\gamma,n)Cu^{62}$ were chosen to monitor the copper and aluminum irradiations, respectively. The products of these reactions have nearly the same half-lives as the products of the reactions which they monitor.[7] Errors caused by fluctuations in x-ray beam intensity during bombardments are thus minimized. The same monitors were also used to compare x-ray intensities during different bombardments at the same energy.

The second method for distinguishing (γ,μ) reactions from (p,n) or (n,p) reactions made use of variations in target thickness. Since a single thin target would not have resulted in sufficiently active samples, the following technique was

[6] L. I. Schiff, Phys. Rev. **70**, 87 (1946).

[7] According to G. T. Seaborg, Rev. Mod. Phys. **16**, 1 (1944) the half-lives are: Zn^{63} 38 minutes, Mg^{27} 10.2 minutes, Cu^{62} 10.5 minutes.

employed: The yield from a thick-target bombardment was compared with that from a similar bombardment in which the thick target was split up into many thin foils. These were lined up in the beam and separated from each other sufficiently so that the protons or neutrons produced in the material on the average spent a smaller fraction of their range in the target than they did in the case of the thick target. When protons were the secondary particles of interest, each foil had to be thin compared to the proton range. With a device of this type the yield of a primary (x-ray induced) reaction should remain the same as with a thick target, provided the total thickness of target material traversed by the beam is the same; but the yield of a secondary reaction should be reduced.

The thin-foil experiments were carried out with 79 circular target foils arranged in a conical envelope of 1.6 degree half-angle whose apex was at the x-ray source. The foil nearest the source was 4.4 cm, the most distant foil 13.1 cm in diameter. The distance between each foil and its nearest neighbors was one-half its radius. One monitor foil was located at the front and one at the rear of the target foils. These served to check alignment, as well as to monitor beam intensity. Each foil was supported by two wire hooks from wires stretched on a Bakelite rack; the whole apparatus was constructed with the minimum amount of material in order to avoid complications due to scattered radiation. Figure 1 is a schematic diagram of the foil arrangement, Fig. 2 a photograph of the apparatus in position in front of the betatron.

A rough calculation shows that, with the arrangement described, secondary (p,n) or (n,p) reactions should occur to only about one-third or one-fourth the extent that they do in a single layer of the same total thickness.

2. Copper Bombardments

The known stable and radioactive isotopes in the region of copper and zinc are shown in Fig. 3. It is seen in this chart that the only isotopes which can result from (γ,μ^-) reactions on copper are Zn^{63} of half-life 38 minutes and Zn^{65} of half-life 250 days. The latter half-life is so long that a detectable amount of this isotope could not be produced in the 60 to 90 minute copper bombardments.

Purity Requirements

A preliminary experiment carried out with CP cuprous oxide as target material resulted in the formation of 38-minute zinc activity. Since Zn^{63} could be formed from zinc impurity (by the reactions Zn^{64} (γ,n); Zn^{66} $(\gamma,3n)$; Zn^{67} $(\gamma,4n)$; etc.) and possibly from gallium or germanium impurities (by such reactions as Ga^{69} $(\gamma,p5n)$ or Ge^{70} $(\gamma,2p5n)$), it appeared necessary to investigate whether the observed Zn^{63} activity could be accounted for in this way.

In order to determine the degree of purity required for the copper targets, a weighed zinc foil was bombarded under the same conditions as the copper targets and the amount of 38-minute zinc activity formed was measured. This experiment indicated that, with the beam intensities usually available,[8] 1 mg of zinc impurity in the target would give rise to 100 to 400 counts per minute of Zn^{63} activity at saturation with the particular G-M counters and counting geometry used. For the same range of beam intensities preliminary experiments indicated yields of about 800 to 3500 counts per minute of Zn^{63} activity at saturation from the bombardment of 30 g of copper. Thus, to be sure that no more

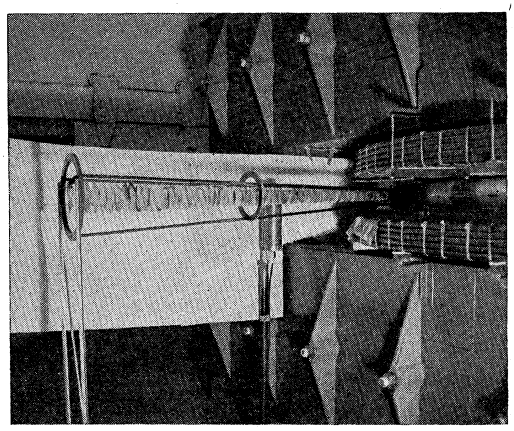

FIG. 2. Apparatus for thin-foil bombardments in position in front of the 100-Mev betatron. A set of copper foils is in place.

[8] 500r to 2000r per minute measured behind $\frac{1}{4}$ inch of lead in the center of the beam one meter from the tungsten target in the betatron.

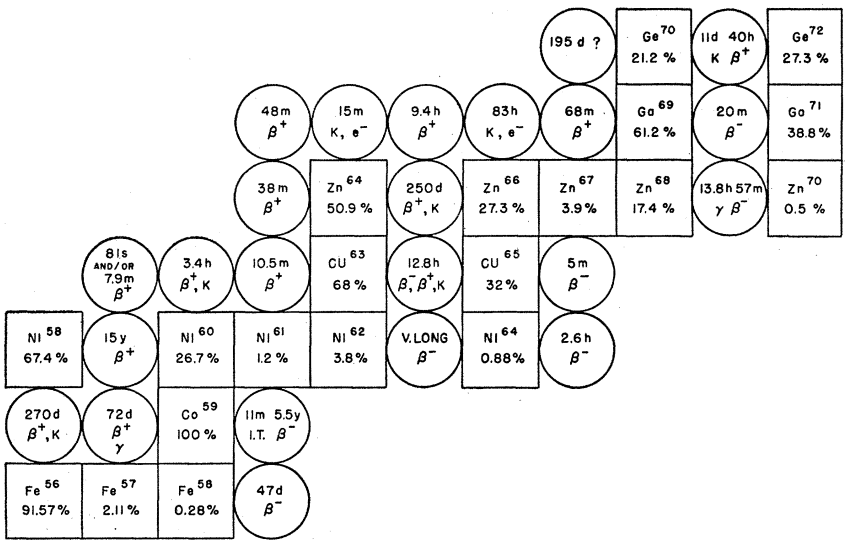

FIG. 3. Known stable and radioactive isotopes in the region of copper. The stable isotopes with their abundances are shown in squares, the radioactive isotopes with their half-lives and modes of decay in circles.

than 1 percent of this effect was attributable to zinc impurity, it was necessary to prove that the copper target contained less than 0.1 mg of zinc per 30 g of copper, less than three parts per million.

No specific determinations of the purity requirements for gallium and germanium were made, but it was felt that these requirements would certainly be much less severe than those for zinc because of the nature of the nuclear reactions which would produce Zn^{63} from these elements.

To be sure that the copper target material could be relied upon to be sufficiently zinc-free, cuprous oxide was prepared from CP cuprous chloride by the following method: The cuprous chloride was dissolved in concentrated hydrochloric acid, reprecipitated by dilution with water, and then washed with distilled water until the washings were neutral to litmus paper; this process was repeated, and the resulting cuprous chloride was converted to cuprous oxide by digesting it with hot $5N$ sodium hydroxide for about 30 minutes. The cuprous oxide was washed with hot water until the washings gave no visible turbidity with silver nitrate solution. To determine the completeness of zinc removal obtained by this method a batch of cuprous oxide was prepared after the addition to the starting material of a known amount of 250-day Zn^{65} tracer; by measuring the chemical yield and the Zn^{65} activity in the cuprous oxide sample obtained, it was found that the zinc content in the copper had been reduced by a factor of at least 4000. The cuprous chloride used as the starting material was known to contain less than 0.1 percent of zinc by weight. Therefore, the tracer experiment showed that the cuprous oxide contained less than 0.35 part per million of zinc. Several other purification procedures tested by the tracer technique described proved much less satisfactory. It should be mentioned that the purification procedure used may also be expected to remove gallium and germanium impurities efficiently. In addition, it seems most unlikely that these elements are present in significant amounts in CP copper salts.

Targets

About 30 g of cuprous oxide prepared by the method described above were used as a target in each of the thick target experiments. Later a supply of copper metal reported by the manufacturers to contain less than one part per million of zinc was obtained from the U. S. Metals Refining Company. This material was rolled[9] to a thickness of about 0.00025 inch (about 5 mg/cm²) and used for the foil bombardments in the apparatus of Figs. 1 and 2. The total thickness of copper traversed by the beam

[9] We are indebted to Messrs. Schermerhorn and Cooley of this laboratory for carrying out this rolling operation.

in the foil experiments was only about 400 mg/cm² while the solid targets were more than four times as thick. The zinc monitor foils had a thickness of 10–14 mg/cm².

Chemical Separations

After each bombardment the zinc activity was isolated chemically from the bombarded copper target and from any radioactive isotopes of other elements which might conceivably have been formed in the bombardment of copper (or cuprous oxide) with the x-ray beam; these other elements are chiefly nickel, cobalt, iron, and manganese.

The following procedure was used for cuprous oxide targets: Cuprous oxide was dissolved in hot concentrated hydrochloric acid containing 250 mg of zinc carrier. The solution was diluted and cuprous iodide precipitated with a small excess of potassium iodide. After centrifugation and neutralization of the supernatant with concentrated ammonia, excess iodine was reduced with hydrazine hydrate. The solution was brought to *p*H 1.0 with hydrochloric acid, and the small amount of copper still in solution was precipitated with hydrogen sulfide. The filtrate from the copper sulfide precipitate was made ammoniacal and then saturated with hydrogen sulfide.[10] The sulfide precipitate was leached with hot 2*N* hydrochloric acid (a small, black residue usually remained), and the hydrogen sulfide was boiled out of the solution. The *p*H was adjusted to 2.5 to 2.7 with 4*M* sodium acetate; 50 mg each of cobalt, nickel, iron, and manganese carriers were added; the solution was heated to boiling; and zinc sulfide was precipitated with hydrogen sulfide. A few milligrams of "Hyflo Supercel" filter aid were added, the precipitate was filtered out and washed, first with 0.1*N* acetic acid saturated with hydrogen sulfide, then with hot acetone. Dry air was then sucked through the precipitate for a short time.

Copper foils were dissolved in an ice-cooled mixture of 12*N* hydrochloric acid and 30 percent hydrogen peroxide (in a volume ratio 2 to 1). Excess peroxide was boiled out, and sufficient potassium iodide was added to reduce all the Cu^{++} to Cu_2^{++} as well as to precipitate cuprous iodide. From this point on the procedure was the same as for cuprous oxide. In either case the entire chemical procedure was performed in 30 to 40 minutes.

The zinc monitor foils were dissolved in hydrochloric acid. A few milligrams of Cu^{++} carrier were added. The H^+ concentration was adjusted to 0.3*N*, and copper sulfide precipitated with hydrogen sulfide. The *p*H of the filtrate was adjusted to 2.5, a few milligrams of Co^{++} and Ni^{++} carriers were added, and hydrogen sulfide was passed in to precipitate zinc sulfide. The precipitate was filtered and dried. In the case of the large monitor of a copper foil bombardment the whole foil was dissolved, but only a 10 to 15 percent aliquot of the solution was processed so that the thickness of the final zinc sulfide precipitate was about the same as that obtained from the small monitor. The chemical yields, both in the target and in the monitor procedures, were determined after the completion of the counting by weighing the dried zinc sulfide precipitates.

Counting

The zinc sulfide samples, obtained from the above procedures, were mounted either on Bakelite cards or, for the weak samples, on $\frac{1}{32}$-inch thick lead squares to increase the counting efficiency by back-scattering. The samples were covered with Cellophane (1 mg/cm²) and placed in a reproducible position under a Geiger-Müller counter. Several different counter tubes were used in the various experiments but they were intercalibrated with Zn^{63} radiation. Decay curves were followed for several half-lives.

3. Aluminum Bombardments

The known stable and radioactive isotopes in the region of aluminum and magnesium are shown in Fig. 4. Aluminum has a single stable isotope and therefore Mg^{27} (half-life 10.2 minutes) is the only product of a (γ,μ^+) reaction to be expected.

Purity Requirements

Mg^{27} could be produced from silicon, phosphorus, or sulfur impurities by the reactions Si^{29} $(\gamma,2p)$; Si^{30} $(\gamma,2pn)$; P^{31} $(\gamma,3pn)$; S^{32} $(\gamma,4pn)$;

[10] This extra step was necessary because the high ionic strength of the solution made the separation of Zn^{++} from Co^{++}, Ni^{++}, Fe^{++}, and Mn^{++} by H_2S precipitation at a controlled *p*H impossible at this point.

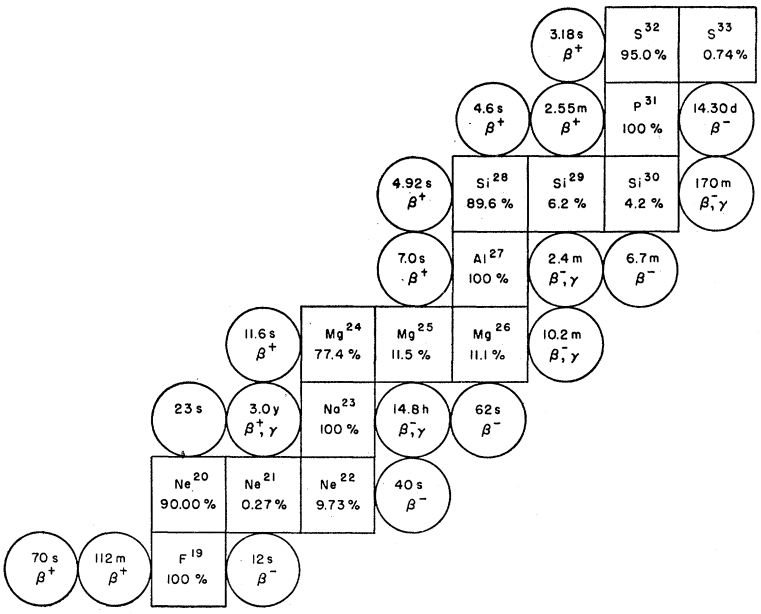

FIG. 4. Known stable and radioactive isotopes in the region of aluminum. The stable isotopes with their abundances are shown in squares, the radioactive isotopes with their half-lives and modes of decay in circles.

S^{33} $(\gamma,4p2n)$; etc. The aluminum used was specially pure metal supplied by the Aluminum Company of America containing less than 0.01 percent of silicon according to the manufacturer's analysis. In view of the low abundance of Si^{29} and Si^{30} this was regarded as a satisfactorily low silicon analysis. No data for the phosphorus and sulfur contents were available; however, these are not common impurities in aluminum, and the reactions resulting in the production of Mg^{27} from these elements by x-rays are probably quite unlikely. Furthermore, the results of the aluminum bombardments described below indicated that most or all of the Mg^{27} formed in thick-target runs resulted from secondary processes rather than from any x-ray induced reactions.

Targets

For the thick-target bombardments stacks of 0.0015-inch aluminum disks were used to facilitate rapid dissolving. The total amount of aluminum used for each bombardment was about 10 g (about 600 mg/cm²). For the foil bombardments the aluminum was rolled to a thickness of about 0.0003 inch (about 2 mg/cm²).[9] Copper monitor foils of about 10 mg/cm² were used.

Chemical Separations

The separation of magnesium from aluminum (and incidentally from sodium and neon) was carried out by the following method: The aluminum was dissolved in hot $12N$ hydrochloric acid containing about 20 mg of magnesium carrier and a small amount of ferrous sulfate as a catalyst. The dissolution was hastened by the gradual addition of 30 percent hydrogen peroxide. The solution was poured into a sufficient excess of $10N$ sodium hydroxide to convert all the aluminum to aluminate ion. The magnesium hydroxide precipitate was centrifuged, the supernatant discarded, and the precipitate dissolved in a small quantity of $6N$ hydrochloric acid. This solution was made ammoniacal (about $0.5M$ in ammonium hydroxide), and magnesium ammonium arsenate was precipitated by the addition of disodium hydrogen arsenate. In the presence of about $0.2M$ tartrate, $1M$ ammonium ion, and 13 percent ethyl alcohol, this precipitation was found to be quite rapid and complete, and aluminum was not carried along. After one minute's stirring the precipitate was filtered, washed successively with ammoniacal tartrate solution, $1M$ ammonia, and acetone, and dried by sucking dry air through it. The entire chemical procedure required 10 to 15 minutes. After the completion of the counting measurements, the chemical yield was found by dissolving the magnesium ammonium arsenate precipitate in hydrochloric acid and determining the magne-

sium content by the 8-hydroxyquinoline method.[11]

The copper activity produced in the copper monitor foils was separated from other possible radioactive products, such as nickel and cobalt, by dissolving the copper in a mixture of 12N hydrochloric acid and 30 percent hydrogen peroxide, boiling off excess peroxide, and precipitating cuprous iodide with a slight excess of potassium iodide in the presence of Ni^{++} and Co^{++} carriers. The cuprous iodide precipitate was filtered, washed with water and alcohol, dried, and mounted for counting. The chemical yield was later determined by drying the cuprous iodide at 105°C, and weighing it.

Counting

The counting was done as described above in case of the copper bombardments.

III. RESULTS

Figures 5 and 6 show typical decay curves of the zinc fractions isolated from a thick cuprous oxide target and from a set of copper foils after bombardment with the 100-Mev x-ray beam.

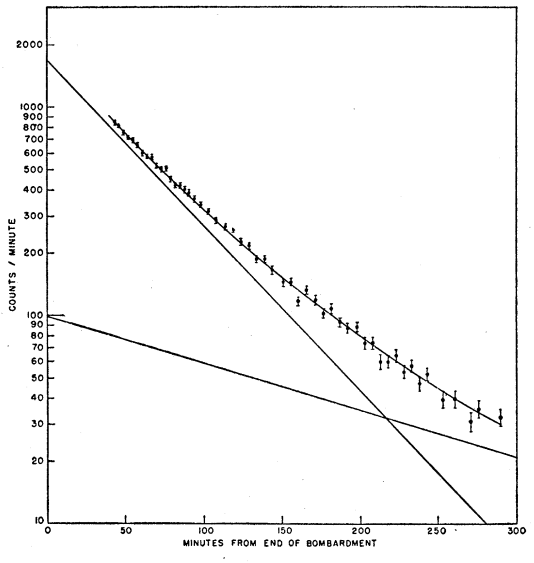

FIG. 5. Decay curve of the zinc fraction isolated from a thick cuprous oxide target bombarded with the 100-Mev x-ray beam.

[11] Kolthoff and Sandell, *Textbook of Quantitative Inorganic Analysis* (The Macmillan Company, New York, 1938), p. 351.

The standard deviations are indicated for all experimental points. Both curves show the presence of an unidentified long-lived (about 2-hour half-life) component. After subtracting this from the experimental decay curve, a 38-minute period is obtained.

Decay curves of the magnesium fractions obtained from typical thick aluminum and aluminum foil bombardments are shown in Figs. 7 and 8, respectively. In this case, no component other than the 10-minute period ascribed to Mg^{27} was found. Again, the counting rates in the foil bombardments were less than 100 counts per minute at the beginning of the counting, and the uncertainty in the position of the decay curve in Fig. 8 is, therefore, relatively large, perhaps ±15 percent.

The results of the six copper bombardments are summarized in Table I. Column 7 gives, for each experiment, the amount of 38-minute zinc activity that would have been obtained if an amount of copper containing one millimole (63 mg) of Cu^{63} per cm^2 had been bombarded to saturation. Similarly, column 11 lists the amount of 38-minute Zn^{63} activity that would have been obtained if an amount of zinc monitor containing one millimole (64 mg) of Zn^{64} per cm^2 had been bombarded to saturation. The values in these columns have all been corrected for counter geometry; they are given for samples mounted in $\frac{7}{8}$-inch diameter circles placed as close as

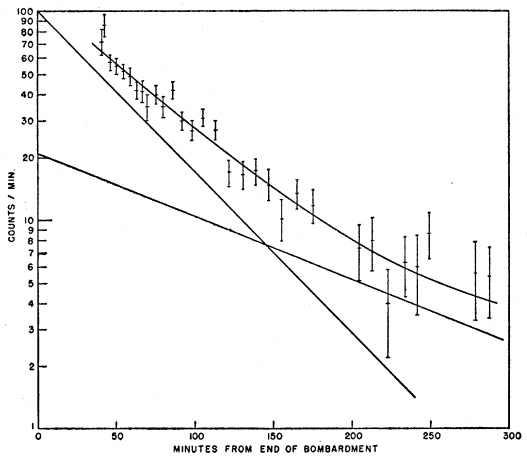

FIG. 6. Decay curve of the zinc fraction isolated from a set of copper foils bombarded with the 100-Mev x-ray beam.

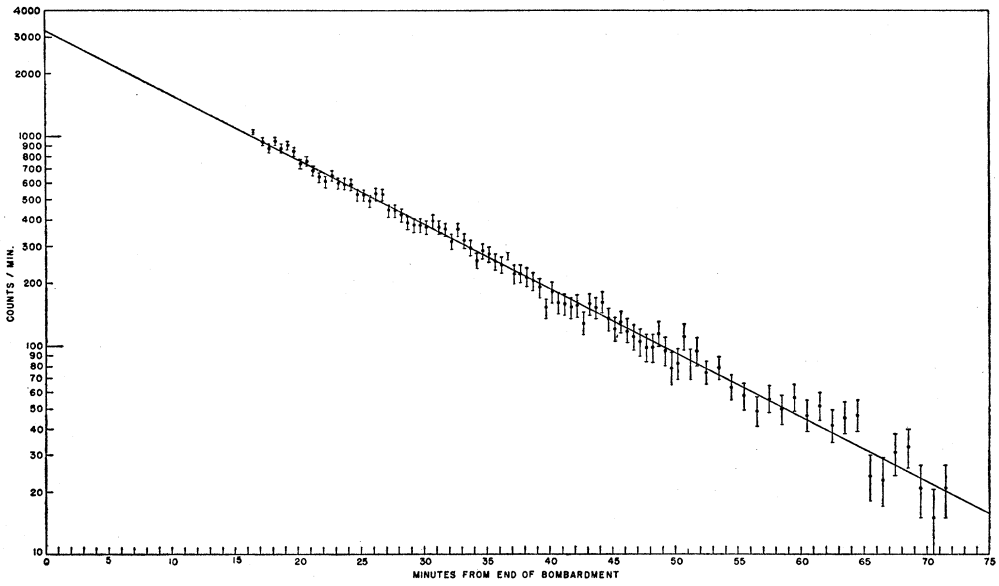

FIG. 7. Decay curve of the magnesium fraction isolated from a thick aluminum target bombarded with the 100-Mev x-ray beam.

possible to the mica window of a conventional bell-type G-M counter and backed by $\frac{1}{32}$ inch of lead. Column 12 lists the ratios of the Zn^{63} activities obtained from target and monitor, and these are the values of interest for deciding on the nature of the reaction leading to the formation of Zn^{63} from copper. For the solid target bombardments this ratio appears to be the same within the experimental errors at 50 and 100-Mev maximum energy. However, a comparison of experiments 1 and 2 with experiments 5 and 6 shows that the production of Zn^{63} from copper is reduced by about a factor of four (relative to the monitor) when a thick target is split up into thin foils. It is estimated that the ratios in column 12 have probable errors of no more than ± 15 percent.

The results of the seven aluminum bombardments are summarized in Table II. This table is arranged in the same way as Table I. Again, the amount of Mg^{27} activity relative to the monitor activity (column 12) is about the same at 50 and 100-Mev maximum bombarding energy (experiments 7 to 11).[12] Splitting the thick target into thin foils (experiments 12 and 13) reduces the Mg^{27} activity by a factor of about 3.5.

[12] The rather large discrepancy between experiment 9 and experiments 10 and 11 is unexplained.

IV. DISCUSSION

The results in Tables I and II indicate clearly that the production of Zn^{63} from thick copper targets and of Mg^{27} from thick aluminum targets in the 100-Mev x-ray beam are not owing to (γ,μ^-) and (γ,μ^+) reactions, respectively, except perhaps to a small extent. In fact, the reduction

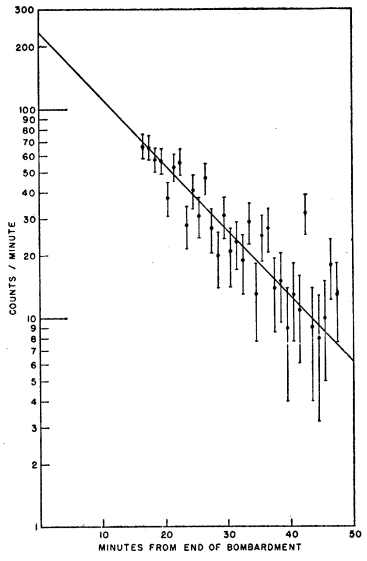

FIG. 8. Decay curve of the magnesium fraction isolated from a set of aluminum foils bombarded with the 100-Mev x-ray beam.

TABLE I. Results of copper bombardments.

1 Exp. No.	2 Max. beam energy Mev	3 Target	4 Millimoles of Cu per cm² of target	5 Counts/min. of Zn^{63} from target (at end of bombardment)	6 Chemical yield of Zn from target (percent)	7 Counts/min. of Zn^{63} from 1 millimole of Cu^{63} per cm² of target*		8 Millimoles of Zn monitor per cm²	9 Counts/min. of Zn^{63} from monitor (at end of bombardment)	10 Chemical yield of Zn from monitor (percent)	11 Counts/min. of Zn^{63} from 1 millimole of Zn^{64} per cm² of monitor*	12 Ratio column 7 / column 11
1	100	Cu_2O	30.7	300	60	65.7		.156	8500	100	3.03×10^5	2.2×10^{-4}
2	100	Cu_2O	27.5	1700	82	161		.199	21,500	93.5	6.40×10^5	2.5×10^{-4}
3	50	Cu_2O	30.5	390	94	45.5		.153	7200	98	2.21×10^5	2.1×10^{-4}
4	50	Cu_2O	28.0	155	63	34.9		.171	4850	99	1.59×10^5	2.2×10^{-4}
5	100	Cu foils	6.24	100	86	39.7	front rear	.198 .211	24,000 3100	90 11.1	7.47×10^5 7.34×10^5	0.54×10^{-4}
6	100	Cu foils	6.24	110	89.5	42.0	front rear	.207 .216	23,000 3400	86 12	7.18×10^5 7.27×10^5	0.58×10^{-4}

* These values are given for saturation bombardment, 100 percent chemical yield, and standard counting geometry on a mica-window counter.

TABLE II. Results of aluminum bombardments.

1 Exp. No.	2 Max. beam energy Mev	3 Target	4 Millimoles of Al per cm² of target	5 Counts/min. of Mg^{27} from target (at end of bombardment)	6 Chemical yield of Mg percent	7 Counts/min. of Mg^{27} from 1 millimole of Al^{27} per cm² of target*		8 Millimoles of Cu monitor per cm²	9 Counts/min. of Cu^{62} from monitor (at end of bombardment)	10 Chemical yield of Cu from monitor (percent)	11 Counts/min. of Cu^{62} from 1 millimole of Cu^{63} per cm² of monitor*	12 Ratio column 7 / column 11
7	100	thick Al	24.6	3200	79.0	220		.181	17,000	43.3	7.81×10^5	2.8×10^{-4}
8	100	thick Al	23.9	3900	85.7	254		.153	15,800	34.6	10.8×10^5	2.4×10^{-4}
9	50	thick Al	24.5	935	83.0	61.3		.177	5400	74.8	1.47×10^5	4.2×10^{-4}
10	50	thick Al	24.9	570	79.0	38.6		.173	5200	79.9	1.36×10^5	2.8×10^{-4}
11	50	thick Al	24.5	770	88.8	47.2		.344	7000	40.8	1.79×10^5	2.6×10^{-4}
12	100	Al foils	5.74	232	80.5	67.0	front rear	.166 .157	25,400 3950	62.6 10.4	7.45×10^5 8.68×10^5	0.83×10^{-4}
13	100	Al foils	5.74	215	85.5	58.5	front rear	.169 .168	36,500 2940	86.4 5.94	9.04×10^5 9.00×10^5	0.65×10^{-4}

* These values are given for saturation bombardment, 100 percent chemical yield, and standard counting geometry on a mica-window counter.

in activity obtained by splitting a thick target into an array of thin foils is consistent with the assumption that the secondary reactions $Cu^{63}(p,n)Zn^{63}$ and $Al^{27}(n,p)Mg^{27}$ are entirely responsible for the production of the two isotopes.[13] If, nevertheless, it is assumed that all the Zn^{63} and Mg^{27} produced in the thin foil bombardments result from (γ,μ) reactions, an upper limit (which is almost certainly set much too high) will be obtained for the ratio of (γ,μ)

[13] In case the secondary bombarding particles are neutrons, as in the aluminum bombardments, the source of the neutrons may not be entirely in the target itself. In an experiment to check this point an aluminum target was bombarded outside the center of the beam in a position where it received only 1/30 as much x-ray intensity as a similar target in the center of the beam. The amount of Mg^{27} produced, however, was reduced only by a factor of two. This indicates that roughly half the Al^{27} (n,p) reactions in the thick-target bombardments were caused by neutrons from sources external to the targets. This does not affect the validity of the conclusion that the Mg^{27} is produced by a secondary rather than a primary reaction.

to (γ,n) cross sections. In both cases this ratio, as taken directly from columns 12 of Tables I and II, is about 5×10^{-5}. If $\sigma_{\gamma,n}$ is assumed to be of the order of magnitude 10^{-25} cm^2 for the betatron x-ray spectrum at 100-Mev maximum energy, this would lead to an upper limit for σ_{γ,μ^+} on Al^{27} and σ_{γ,μ^-} on Cu^{63} of 10^{-29} to 10^{-30} cm^2 for the same spectrum. This, of course, does not mean that the cross sections for (γ,μ) reactions may not be much higher in an energy range where the reactions are possible (if, indeed, they are possible). It does mean that the threshold for (γ,μ) reactions is probably not much below, and may well be above 100 Mev.

It should be pointed out that the radiochemical method described compares very favorably in sensitivity with a cloud-chamber search for meson production processes. If in going from thick to thin targets, the yields of Mg^{27} and Zn^{63} had been reduced by only a small factor such as 1.5, this would be taken as evidence for the occurrence of (γ,μ) reactions. Taking this as a criterion one can calculate a lower limit for the number of gamma-meson processes which could be detected in any x-ray bombardment by the method described. Using this number[14] and comparing the geometrical arrangements and beam intensities used in the present investigation with those used in recent cloud-chamber studies of heavily ionizing particles produced by the 100-Mev betatron,[15] one arrives at a measure of the relative sensitivity of the two methods. This comparison, which involves no assumptions about cross sections, shows that at the limit of sensitivity of the radiochemical method about 15,000 cloud-chamber pictures would be necessary on the average to show one meson track.

It may be, of course, that mesons can be produced by nuclear processes other than simple (γ,μ) reactions. If it should turn out that the production of mesons can occur in pairs only i.e., by $(\gamma,\mu^+\mu^-)$ reactions, the products of such reactions will be indistinguishable from the target nuclei and the radiochemical method will fail. Another possibility is that mesons may be emitted singly but accompanied by heavy particles. The methods described can easily be extended to (γ,μ^-n) and (γ,μ^+p) reactions. However, the product of a (γ,μ^-p) reaction is identical with that of a (γ,n) reaction, and the product of a (γ,μ^+n) reaction is indistinguishable from that of a (γ,p) reaction. These considerations can readily be extended to more complex cases.

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[14] This turns out to be about 100,000 for Zn^{63} and about 25,000 for Mg^{27} with a 15 percent counting geometry.

[15] G. S. Klaiber, E. Luebke, and G. C. Baldwin, in press.

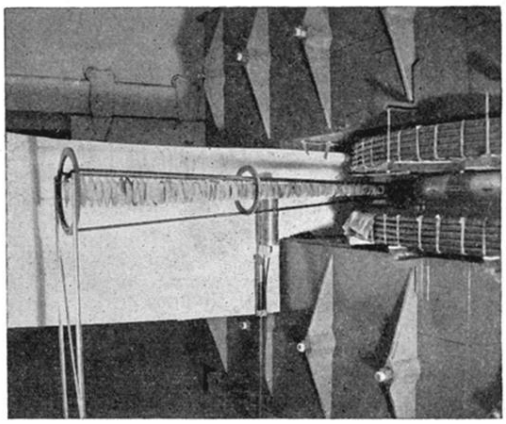

FIG. 2. Apparatus for thin-foil bombardments in position in front of the 100-Mev betatron. A set of copper foils is in place.