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Relative Yields of Some X-Ray Induced Nuclear Reactions

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X-rays from the 100-Mev betatron and 80-Mev synchrotron were used to induce (γ,n), (γ,p), $(\gamma,2n)$, and $(\gamma,2p)$ reactions. Relative yields for a number of these reactions were determined by measurement of the activities of the products. Yields of (γ,n) reactions appear to be about an order of magnitude larger for $Z \geq 29$ than for lower Z; the transition seems to be abrupt. The five (γ,p) reactions studied have approximately equal yields, and these are about the same as (γ,n) yields below the transition. Values for the few $(\gamma,2p)$ yields measured are about one-twentieth those for the (γ,p) reactions. Yields for the $(\gamma,2n)$ reactions vary, but are much smaller than (γ,n) yields. The most probable number of particles emitted as the result of the interaction of a high energy quantum with a nucleus is one.

I. INTRODUCTION

QUANTITATIVE studies of yields of various nuclear reactions involving the emission of a single particle under excitation by 17-Mev and 12-Mev gamma-rays have been made by several investigators.[1-3] Measurements made in this laboratory[4] have shown that many nuclear reactions can be induced by the x-rays produced in the 100-Mev betatron.

In the experiments reported in this paper various elements were irradiated with x-rays generated by the 100-Mev betatron in order to study relative yields of (γ,n), (γ,p), $(\gamma,2n)$, and $(\gamma,2p)$ reactions and to see how the yields vary with atomic or mass number. The yield was determined essentially by identification and measurement of the beta-activity of the isotope expected to result from a particular reaction on one of the target isotopes. Experiments were made with x-rays produced in a tungsten target by 50-Mev and by 100-Mev electrons.

In all experiments the beta-activity of the product was distinguished from other activities by analyses of decay curves. Cases for investigation were chosen so as to eliminate or minimize the following possibilities: First, the product could have been made from the target isotopes or impurities by processes other than the particular one of interest; second, other products of half-life similar to the one sought could have been made either from the target elements or from impurities. In order that relative yield values based on counting data might be reliable, insofar as available information permitted, cases were chosen in which decay schemes are known and in which no significant fraction of the counting rates could be ascribed to gamma- or x-ray emission.

II. EXPERIMENTAL DETAILS

Monitors

Irradiations were monitored by measurement of the C^{11} or F^{18} activity induced in a standard square piece of polystyrene or lithium fluoride which was bombarded together with each target. The use of a monitor whose half-life approximates that of the product to be measured reduces errors caused by fluctuations in the x-ray intensity. The two monitors were carefully intercalibrated at both x-ray energies by measurements of the activities produced in them when they were bombarded together for ten minutes at nearly constant intensity. The monitors presented to the beam the same cross section as did targets, and monitor and target were always mounted in tandem. Typical monitor decay plots are shown in Figs. 1 and 2. Except for some short-lived activities in the lithium fluoride, which were not evident one hour after bombardment, only a single radioactive species was observed in each monitor over at least five half-lives.

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[1] W. Bothe and W. Gentner, Zeits. f. Physik **106**, 236 (1937), and Zeits. f. Physik **112**, 45 (1939).

[2] O. Huber, O. Lienhard, P. Scherrer, and H. Wäffler, Helv. Phys. Acta **16**, 33 (1943).

[3] O. Huber, O. Lienhard, and H. Wäffler, Helv. Phys. Acta **17**, 195 (1945); (a) O. Hirzel and H. Wäffler, Helv. Phys. Acta **20**, 373 (1947).

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

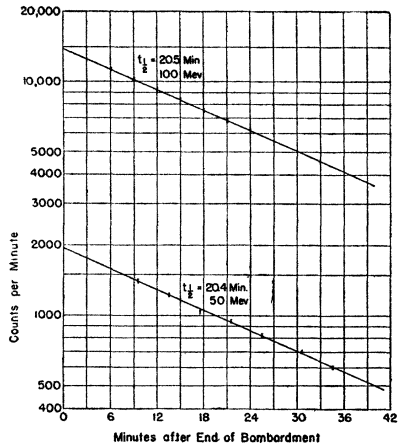

FIG. 1. Decay of polystyrene monitor after irradiation with 100-Mev and with 50-Mev x-rays.

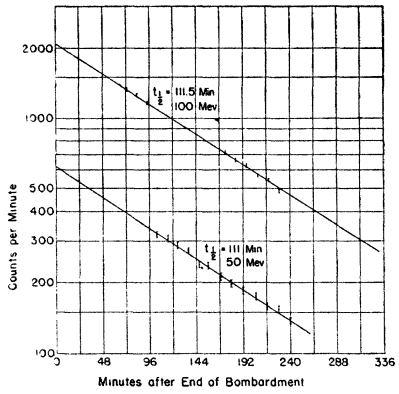

FIG. 2. Decay of lithium fluoride monitor after irradiation with 100-Mev and with 50-Mev x-rays.

The ratio of the saturation activity of the polystyrene monitor to that of the lithium fluoride monitor was 4.39 ± 0.1 at 100 Mev; at 50 Mev it was 3.98 ± 0.1 It happens that monitor activities in all experiments reported here were measured with a lead tetramethyl filled, Eck and Krebs type, cylindrical, thin glass Geiger counter, whose efficiency was checked before each experiment and remained essentially unchanged throughout this research.

Targets and Samples

Most target materials were in the form of powders, which were packed for irradiation in plastic boxes $\frac{3}{4}$ inch by $\frac{3}{4}$ inch in inside section. In the standard bombardment geometry the axis of the x-ray beam passed through the centers of both box and monitor. The distance from the x-ray source was 80 centimeters. After irradiation the powder or a part of it was poured into a short vertical brass cylinder $\frac{7}{8}$ inch in inside diameter, which was previously positioned on a plastic sample mounting board. A closely fitted, flat-faced plunger, hand operated, served to form the powder into a fairly uniform pill even when the thickness was not over 0.2 millimeter. After removal of plunger and cylinder the samples were covered with thin Cellophane.

After the counting experiments on a given sample had been concluded, the weight of target material in the sample was determined. In most cases the sample was dried to constant weight, either in a desiccator or an oven, and weighed. Where a different method of assay was used this will be indicated in the discussion of the individual results below.

Counters and Recorder

For measurement, samples were always placed in a standard position very close to the mica window of a G-M tube of $1\frac{1}{16}$-inch inside diameter filled with argon and ethyl alcohol. The pulses from the counter, after amplification, were put into a scaler whose factor could be chosen from the powers of two up to a maximum of 4096. The output of the scaler was recorded on the moving paper tape of a Brush Type BL-201 oscillograph. The tape used on this machine is ruled, and it is moved under the galvanometer pen by a geared synchronous motor at one of three speeds. By proper choice of scaling factor and paper speed it was possible to follow the decay of activities with half-lives as short as a few seconds. The combination of instruments proved convenient also for recording measurements over extended periods on long-lived samples.

Counting measurements were corrected for small day-to-day variations in counter sensitivity, for back-scattering, for self-absorption, and for absorption in the Cellophane covering and mica window. For the latter absorption correction the mass absorption coefficients of Cellophane and of mica were taken to be the same as that of aluminum.

Absorption and Scattering Measurements

Self-absorption corrections were determined experimentally. Samples of nickel, lithium flu-

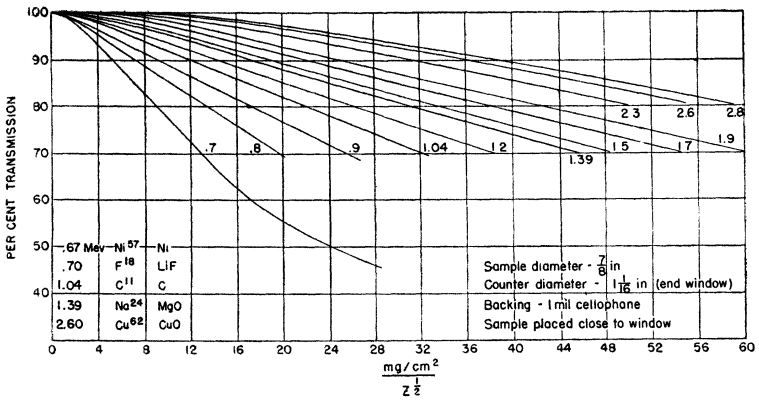

FIG. 3. Self-absorption of beta-radiations of various energies (Mev).

oride, carbon, magnesium oxide, and cupric oxide were irradiated to produce in them, respectively, the activities of $Ni^{57}(\beta^+$ 0.67 Mev), $F^{18}(\beta^+$ 0.7 Mev), $C^{11}(\beta^+$ 0.99 Mev),[5] $Na^{24}(\beta^-$ 1.39 Mev), and $Cu^{62}(\beta^+$ 2.6 Mev). A number of samples of different thicknesses were made from each of the active substances. These samples were mounted by the standard technique except that they were supported on 0.001-inch Cellophane to decrease back-scattering. In some cases it was necessary to allow interfering activities to die so that substantially a single radioactive species might be present in each of the substances at the time of measurement. The activities of the different samples from a single bombardment were measured in the standard geometry under a mica-window counter, and their specific activities, after correction for decay, were plotted against their weights per unit area. The curve obtained was extrapolated to zero thickness. The specific activities were then converted to transmission values. This procedure was followed for each of the substances listed above. Since this list, however, did not include all the active substances measured in the yield experiments, it was assumed that the mass absorption for a given energy is inversely proportional to $\bar{Z}^{\frac{1}{2}}$, the square root of the average atomic number of the absorbing substance. For a compound the average atomic number is the weighted average of the atomic numbers of the elements composing the compound; for example, $\bar{Z}^{\frac{1}{2}}$ for antimony trioxide (Sb_2O_3) is $(2\times122\times51^{\frac{1}{2}}+3\times16\times8^{\frac{1}{2}})/292$ or 6.42. The validity of this assumption is supported by the fact that the two self-absorption curves—transmission *vs.* $(mg/cm^2)/\bar{Z}^{\frac{1}{2}}$—for the 0.67-Mev positron of Ni^{57} in nickel metal and for the 0.7-Mev positron of F^{18} in lithium fluoride were the same within experimental error. By interpolation, curves were obtained for beta-radiations of energies other than those listed. The final results are shown in Fig. 3.

Back-scattering was determined for many of the samples used in the self-absorption experiments by measurement of their activities with thin Cellophane backing and with the standard plastic sheet backing. This small correction, whose maximum value was six percent, was assumed to be a function of transmission only.

The experiments for the determination of the absorption and back-scattering effects are not refined; however, the corrections to observed counting rates contributed by these effects are nearly always under 30 percent. The inaccuracy in these corrections probably gives rise to an error in the final results no greater than five percent.

III. CALCULATION OF RESULTS

The decay curves of most irradiated samples showed the presence of more than one component, as had been expected. The activity at the end of bombardment of the component sought was determined by extrapolation. This value was used to calculate the activity which would be measured under the standard conditions at the end of a saturation bombardment if there were no absorption or back-scattering and if the product from one milligram-atom of the parent isotope were present.

[5] Actually a value of 1.04 Mev for the maximum energy of the C^{11} positron would be more consistent with our other results than the value of 0.99 Mev found by K. Siegbahn and E. Bohr, Ark. f. Mat. Astr. Fys. **30B**, No. 3 (1943).

The procedure for the monitor was simply to determine its activity at the end of bombardment and to calculate the activity for saturation bombardment. The ratio of the saturation product activity per milligram-atom of parent isotope to the saturation activity of C^{11} in the polystyrene monitor was taken as a measure of the yield of a reaction.

IV. RESULTS[6]

Relative yield values are given in Tables I, II, and III. Unless otherwise noted, each yield value listed is the average of at least two independent experiments.

A. (γ,n) Reactions

$C^{12}(\gamma,n)C^{11}$.—Spectroscopically pure graphite powder was used as target material. A typical bombardment lasted 15 minutes. The activity produced decayed with the C^{11} period over at least five half-lives; no other periods were observed.

$N^{14}(\gamma,n)N^{13}$.—In 15-minute bombardments of ammonium chloride the only activities observed were those of N^{13} (9.9 minutes) and Cl^{34} (33 minutes).

$O^{16}(\gamma,n)O^{15}$.—Boric acid was used as the target material. It was analyzed for oxygen by the titration of a weighed quantity with NaOH after the addition of mannitol. In addition to the strong O^{15} activity a weak activity whose half-life was approximately 20 minutes was observed (perhaps C^{11}). Bombardments were of five minutes duration.

$F^{19}(\gamma,n)F^{18}$.—Pure LiF powder made from optical crystal scrap was bombarded for two hours in a typical case. An unidentified 15-minute activity, a 1-minute activity (probably F^{17}), and the strong 110-minute F^{18} were observed. The shorter periods were unobservable after they had decayed for 90 minutes.

$Al^{27}(\gamma,n)Al^{26}$.—For the measurement of the 7-second Al^{26} the counting equipment was placed in a small room off the betatron space. It was not possible to redistribute the target material before counting. The target was in the form of a very pure aluminum disk whose diameter was $\frac{7}{8}$ inch, the same as that of a standard counting sample. The standard monitor was not used; instead a thin $\frac{7}{8}$-inch disk of polythene, $(CH_2)_n$, was bombarded for two minutes together with the aluminum. It proved possible to have the aluminum under the counter within 8 to 10 seconds after the end of irradiation. The 7-second Al^{26} and 62-second Na^{25} activities were easily measurable in the aluminum. The pure C^{11} activity of the polythene was determined with an end-window counter, and the ratio of the yield of the reaction $Al^{27}(\gamma,n)Al^{26}$ to that of the reaction $C^{12}(\gamma,n)C^{11}$ was calculated. This in turn made it possible to calculate the $Al^{27}(\gamma,n)$ yield in terms of the usual polystyrene monitor activity.

$P^{31}(\gamma,n)P^{30}$.—Red phosphorus, which had been washed to remove oxides and acids, was bombarded for five to ten minutes. The activities of P^{30} (2.5 minutes) and Al^{29} (6.7 minutes) were observed, perhaps together with a very small activity of longer half-life.

$Cl^{35}(\gamma,n)Cl^{34}$.—Data on yields of this reaction were obtained from the ammonium chloride bombardments described under $N^{14}(\gamma,n)N^{13}$ and from 10-minute bombardments of potassium chloride. In the potassium chloride the activities of K^{38} and Cl^{34} were the only ones observed.

$K^{39}(\gamma,n)K^{38}$.—Cf. $Cl^{35}(\gamma,n)Cl^{34}$.

$Ni^{58}(\gamma,n)Ni^{57}$.—Pure nickel powder was bombarded for two or three hours. In addition to an unidentified activity of comparatively short half-life only 36-hour Ni^{57} and 1.73-hour Co^{61} were observed.

$Cu^{63}(\gamma,n)Cu^{62}$.—Irradiation of reagent grade CuO for ten minutes produced in measurable quantities the activities of Cu^{62} and O^{15}. A longer period of very low intensity was also present.

$Ga^{69}(\gamma,n)Ga^{68}$ and $Ga^{71}(\gamma,n)Ga^{70}$.—Ga_2O_3 was used as the target material for irradiations of five to twenty minutes duration. In addition to a short-lived activity, only 68-minute Ga^{68} and 20-minute Ga^{70} were observed to be present.

$Pd^{110}(\gamma,n)Pd^{109}$.—After the shorter-lived products formed in the irradiation of $PdCl_2$ had disappeared, the 13-hour Pd^{109} and 35-hour Rh^{105} remained. Because of the thickness of the samples used and because of the presence of conversion electrons in the radiation from Rh^{105}, no (γ,p) yield was calculated on the basis of the

[6] Preliminary reports on some of these results have been made. Cf. M. L. Perlman and G. Friedlander, Phys. Rev. **72**, 1272 (1947); G. Friedlander and M. L. Perlman, Bull. Am. Phys. Soc. **23**, No. 2, 38 (Jan. 1948).

TABLE I. Relative yields of (γ,n) reactions; $N^{14}(\gamma,n)N^{13}=1.00$ at each energy.

Parent isotope	Product isotope	Product[a] half-life	Product[b] betas and energies (Mev)	Relative yield 100 Mev	50 Mev
$_6C^{12}$	C^{11}	20.5 min.	β^+ 1.04[h]	2.3	2.3
$_7N^{14}$	N^{13}	9.9 min.	β^+ 1.2[g]	*1.00*	*1.00*
$_8O^{16}$	O^{15}	2.1 min.	β^+ 1.7	2.2	2.4
$_9F^{19}$	F^{18}	1.87 hr.	β^+ 0.7	2.7	2.8
$_{13}Al^{27}$	Al^{26}	7.0 sec.	β^+ 2.99	2.3	3.1
$_{15}P^{31}$	P^{30}	2.5 min.	β^+ 3.0	7.2	7.1
$_{17}Cl^{35}$	Cl^{34}	33.0 min.	β^+ 5.1 (80%)[c] 2.4 (20%)	2.4	2.4
$_{19}K^{39}$	K^{38}	7.6 min.	β^+ 2.5[d]	2.6	2.6
$_{28}Ni^{58}$	Ni^{57}	36.0 hr.	β^+ 0.67	6.3	6.0
$_{29}Cu^{63}$	Cu^{62}	9.9 min.	β^+ 2.6	33	35
$_{31}Ga^{69}$	Ga^{68}	68.0 min.	β^+ 1.9	42	44
$_{31}Ga^{71}$	Ga^{70}	20.0 min.	β^- 1.7	43	44
$_{46}Pd^{110}$	Pd^{109}	12.7 hr.	β^- 1.1[e]	33	39
$_{47}Ag^{109}$	Ag^{108}	2.33 min.	β^- 2.8	41	46
$_{51}Sb^{121}$	Sb^{120}	16.6 min.	β^+ 1.53	42	46
$_{75}Re^{187}$	Re^{186}	92.0 hr.	β^- 1.07[f]	85	86

[a] Values observed in these experiments.
[b] Unless noted data from G. T. Seaborg, Rev. Mod. Phys. **16**, 1 (1944).
[c] Ho Zah-Wei, Phys. Rev. **70**, 782 (1947).
[d] M. M. Ramsey, J. L. Meem, and A. C. G. Mitchell, Phys. Rev. **72**, 639 (1947).
[e] W. Rall, Phys. Rev. **70**, 112A (1946).
[f] D. C. Hess, Jr., R. J. Hayden, and M. G. Inghram, Phys. Rev. **72**, 730 (1947); L. J. Goodman and M. L. Pool, Phys. Rev. **71**, 288 (1947).
[g] K. Siegbahn and S. E. Peterson, Ark. f. Mat. Astr. o Fys. **32A**, No. 9 (1945); **32B** No. 5 (1945); L. M. Langer, C. S. Cook, and M. B. Sampson, Phys. Rev. **71**, 906 (1947).
[h] See reference 5.

35-hour activity. Duration of bombardments was two to three hours.

$Ag^{109}(\gamma,n)Ag^{108}$.—In short irradiations (one to two minutes) of pure silver powder only 2.3-minute Ag^{108} and 24.3-minute Ag^{106} were observed.

$Sb^{121}(\gamma,n)Sb^{120}$.—The target material was antimony trioxide (Sb_2O_3); duration of bombardment was ten minutes. Three products were observed, 2-minute O^{15}, 16.6-minute Sb^{120}, and a long-lived activity of very low intensity which may have been Sb^{122}. No 117-minute In^{117}, which would be produced in the reaction $Sb^{121}(\gamma,\alpha)In^{117}$, was observed.

$Re^{187}(\gamma,n)Re^{186}$.—Rhenium estimated to be 99.99 percent pure[7] was bombarded for five hours. Two LiF monitors were used, one for the first half and one for the last half of the irradiation. After approximately three days the samples decayed with the 92-hour half-life characteristic of Re^{186}.

In Table I are given yield values for the (γ,n) reactions observed in the irradiations described above. The yield value of the reaction $N^{14}(\gamma,n)N^{13}$ has arbitrarily been taken as unity at each x-ray energy, and all other yield values are relative to it. Limits of errors are estimated to be ± 15 percent. Figure 4 shows the relative yields of the (γ,n) reactions plotted against mass number.

B. (γ,p) Reactions

$Si^{30}(\gamma,p)Al^{29}$.—In very pure elementary silicon which was bombarded for 15 minutes the activities of Al^{29} (6.7 minutes) and of Al^{28} (2.4 minutes) only were observed. A small amount of 10-minute Mg^{27} may have been present. As in many of these experiments, activities of half-life shorter than approximately 30 seconds decayed to a quite low level during the time interval between the end of bombardment and the start of measurement.

$Fe^{57}(\gamma,p)Mn^{56}$.—The target material chosen was metallic iron powder, which was analyzed for oxide content. Bombardment time was two hours. Besides some short periods (probably those of Fe^{53} and Mn^{52}) the only activities observed were 2.6-hour Mn^{56} and perhaps[15] 8-hour Fe^{52}.

$Ni^{62}(\gamma,p)Co^{61}$.—Cf. $Ni^{58}(\gamma,n)Ni^{57}$.

$Mo^{98}(\gamma,p)Cb^{97}$.—In samples of MoO_3 bombarded for one hour there were observed activities of 15-minute and 75-minute half-lives (the latter Cb^{97}) and an activity of low intensity and comparatively long half-life.

$Ru^{102}(\gamma,p)Tc^{101}$.—Ruthenium metal was bombarded for ten minutes. In addition to the

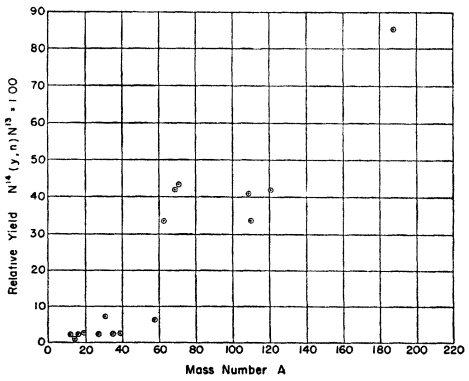

FIG. 4. Relative yields of (γ,n) reactions induced by 100-Mev x-rays.

[7] Obtained from Jarrell-Ash Company, Boston, Massachusetts.

[15] Cunningham, Hopkins, Lindner, Miller, O'Connor, Perlman, Seaborg, and Thompson, Phys. Rev. **72**, 739 (1947).

14-minute Tc^{101}, activities of the following half-lives were present: approximately 3 minutes, 80 minutes, comparatively long.

Yields of the (γ,p) reactions relative to the (γ,n) yield of N^{14} are given in Table II.

C. $(\gamma,2n)$ and $(\gamma,2p)$ Reactions

$C^{12}(\gamma,2n)C^{10}$.—Polystyrene targets in the form of disks were irradiated for 20 seconds. The experimental arrangements and monitoring were similar to those used for the $Al^{27}(\gamma,n)Al^{26}$ measurements. An aluminum absorber of 110-mg/cm² thickness served to decrease the background C^{11} activity. Very little, if any, C^{10} decay (8.8-second half-life) was observed in the curve obtained by the addition of five experiments. Only an upper limit could therefore be set for the relative yield of the reaction.[8]

$F^{19}(\gamma,2n)F^{17}$.—Measurements on the production of the 70-second F^{17} activity from F^{19} were made on LiF samples which were irradiated for two minutes. See $F^{19}(\gamma,n)F^{18}$.

$P^{31}(\gamma,2n)P^{29}$.—The half-life of P^{29} (4.6 seconds) precluded the use of the usual mechanical transfer of samples to the counter. Red phosphorus with one percent of polystyrene to act as binder was formed into flat pellets $\frac{7}{8}$ inch in diameter whose transmission for the radiations both of P^{29} and P^{30} was over 90 percent. Several pellets were placed side by side in a line along the axis of the 80-Mev x-ray beam of the synchrotron. Just above the phosphorus there was mounted a cylindrical thin-walled counter which was shielded from the direct beam by several inches of lead. The samples were irradiated for ten seconds and counted automatically immediately afterwards. A decaying background, measured in irradiations made without phosphorus, was taken into account. The observed P^{30} activity was used as an "internal" monitor. Little or no 4.6-second P^{29} was observed, and the value for the relative yield given is an upper limit. This value is calculated on the assumption that the relative yield of the reaction $P^{31}(\gamma,n)P^{30}$ is about the same at 80-Mev as at 50-Mev and at 100-Mev.

[8] If the half-life of C^{10} is 20 seconds (rather than 8.8 seconds), as has been recently suggested (R. Sherr, H. R. Muether, and M. G. White, Bull. Am. Phys. Soc. **23**, No. 3, 45 (1948)), the upper limit of the yield is affected very little.

TABLE II. Relative yields of (γ,p) reactions; $N^{14}(\gamma,n)N^{13}=1.00$ at each energy.

Parent isotope	Product isotope	Product half-life	Product betas and energies (Mev)	Relative yield 100 Mev	50 Mev
$_{14}Si^{30}$	Al^{29}	6.8 min.	β^- 2.5	5.8	6.6
$_{26}Fe^{57}$	Mn^{56}	2.62 hr.	β^- 0.75 (20%) 1.04 (30%)[a] 2.81 (50%)	7.6	7.6
$_{28}Ni^{62}$	Co^{61}	1.74 hr.	β^- 1.1	5.4	5.0
$_{42}Mo^{98}$	Cb^{97}	76.0 min.	β^- 1.4[b]	5.0	3.1
$_{44}Ru^{102}$	Tc^{101}	14.5 min.	β^- 1.2	3.7	3.6[c]

[a] K. Siegbahn, Arkiv f. Mat. Astr. o. Fys. **33A**, No. 10 (1946).
[b] Plutonium Project, J. Am. Chem. Soc. **68**, 2411 (1946).
[c] Value based on one experiment.

$Cu^{63}(\gamma,2n)Cu^{61}$.—Cupric oxide which was irradiated for two hours showed, in addition to the short-period activities previously described, the activities of Cu^{61} (3.2 hours) and Cu^{64} (12.8 hours). Because of the large self-absorption of the radiations of Cu^{64} in the sample, its activity was not used to calculate the (γ,n) yield on Cu^{65}. In order to see whether the 3.2-hour Cu^{61} might not be masking 1.75-hour Co^{61} produced by $(\gamma,2p)$ reaction, in one experiment a chemical separation was carried out. The cobalt fraction at saturation was only about 7 percent as active as the Cu^{61}.

$Al^{27}(\gamma,2p)Na^{25}$.—Cf. $Al^{27}(\gamma,n)Al^{26}$.

$P^{31}(\gamma,2p)Al^{29}$.—Cf. $P^{31}(\gamma,n)P^{30}$.

$Cu^{63}(\gamma,2p)Co^{61}$.—Cf. $Cu^{63}(\gamma,2n)Cu^{61}$. It is not clear how much of the Co^{61} was produced by the (γ,α) reaction on Cu^{65}.

In Table III there are given yields of the two-particle reactions, again relative to that of the $N^{14}(\gamma,n)$ reaction.

TABLE III. Relative yields of $(\gamma,2n)$ and $(\gamma,2p)$ reactions yield of $N^{14}(\gamma,n)N^{13}=1.00$ at each energy.

Reaction	Product half-life	Product betas and energies (Mev)	Relative yield 100 Mev	50 Mev
$C^{12}(\gamma,2n)C^{10}$	not observed	β^+ 3.4	<0.003	
$F^{19}(\gamma,2n)F^{17}$	72.0 sec.	β^+ 2.1	0.22	0.15
$P^{31}(\gamma,2n)P^{29}$	not observed	β^+ 3.6	<0.1[c]	
$Cu^{63}(\gamma,2n)Cu^{61}$	3.2 hr.	β^+ 0.9 (78%)	3.3	2.5
$Al^{27}(\gamma,2p)Na^{25}$	62.0 sec.	β^- 2.7 (45%)[a] 3.7 (55%)	0.15	0.14
$P^{31}(\gamma,2p)Al^{29}$	6.7 min.	β^- 2.5	0.20	0.15[d]
$Cu^{63}(\gamma,2p)Co^{61}$	1.8 hr.	β^- 1.1[b]		0.16[d]

[a] E. Bleuler and W. Zünti, Helv. Phys. Acta, **20**, 195 (1947).
[b] T. J. Parmley and B. J. Moyer, Phys. Rev. **72**, 82 (1947).
[c] 80-Mev x-ray energy.
[d] Value based on one experiment.

V. DISCUSSION

Preliminary measurements[9] indicate that the spectral distribution of quanta in the 100-Mev x-radiation from the betatron is in at least approximate agreement with theoretical predictions; that is, the number of quanta in a small energy interval is inversely proportional to the mean energy of the interval. As yet accurate measurements are not available of relative intensities, in terms of quanta, at various x-ray energies. For this reason it is difficult to compare on an absolute basis yields obtained at different energies, and therefore one of the (γ,n) yields has been taken as unity at each energy.

The neutrons and protons produced by the x-rays in the target and in the surroundings do cause some nuclear reactions. The yields of two such secondary reactions, $Cu^{63}(p,n)Zn^{63}$ and $Al^{27}(n,p)Mg^{27}$, in thick targets have been found[10] to be about 2×10^{-4} times those of primary (γ,n) reactions on copper and zinc. It is unlikely, therefore, that secondary processes can be responsible for any significant fraction of the yields of even the relatively improbable reactions studied. Another experiment involving the simultaneous exposure of samples in and outside the center of the x-ray beam set an upper limit at 1 percent for the fraction of the apparent "(γ,n) yields" which may actually be due to $(n,2n)$ reactions.

The apparently sudden increase in the (γ,n) yield, which occurs in the neighborhood of mass 60, is unexplained. It has been suggested that it may be related to the fact that in the cases investigated (Table I) the neutron excess $(A-2Z)$ is two or less for the target nuclei with masses below 60 and five or more for target nuclei with masses above 60. This explanation would not seem to agree with the fact that the yields for the two gallium isotopes are the same and the fact that no substantial changes in (γ,n) yields were observed between Cu^{63} with a neutron excess of five and Pd^{110} with a neutron excess of eighteen. Additional measurements should help to clarify this point. The high yield of the $Re^{187}(\gamma,n)$ reaction (about twice that of any other reaction studied) suggests that other cases above $A=120$ should also be investigated.

Although the five (γ,p) reactions studied involve target elements whose (γ,n) yields differ by large factors, no such differences appear in the (γ,p) yields. The values for the (γ,p) yields are of the same order as the (γ,n) yields for the species below copper. It seems hard to reconcile this result with the idea of evaporation from a compound nucleus.

The $(\gamma,2p)$ and $(\gamma,2n)$ yields are much lower than single-particle yields. That at least some three-particle yields are quite low also is evident from the fact that the (γ,n) yields from the two gallium isotopes are the same. The magnitudes of the relative (γ,n) yields from Cl^{35}, Cu^{63}, and Sb^{121}, in which cases the product could have been produced by $(\gamma,3n)$ reaction from the accompanying isotopes richer by two neutrons, also show that $(\gamma,3n)$ is a relatively improbable reaction.

The fact that the relative yields for the various (γ,n) and (γ,p) reactions follow, within experimental error, the same trend at 50-Mev as they do at 100-Mev maximum energy suggests either that quanta above 50-Mev in energy do not contribute very much to the (γ,n) yield or that the excitation curves (cross section *versus* photon energy) are similar except for an energy independent parameter. The first possibility is substantiated by some excitation measurements[11] for the reactions $Cu^{63}(\gamma,n)Cu^{62}$ and $C^{12}(\gamma,n)C^{11}$.

Further work on the yields of photo-nuclear reactions is clearly necessary. In particular, an extension of this research to reactions involving the emission of more than two nucleons, further studies on the dependence of yield on mass number, and investigations of excitation functions appear desirable.

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[9] Private communication from Dr. J. L. Lawson.

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