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Photo-induced Reaction $Cu^{63}(\gamma, n)Cu^{62}$ produced by the Gamma-Rays of Lithium bombarded with High Speed Protons*

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Abstract

We observed $Cu^{63}(\gamma, n)Cu^{62}$ reaction produced by the gamma-rays emitted from lithium bombarded with 460 Kev protons, and a fairly accurate value of the cross section for this reaction was determined by the measurements of the induced positron activities produced in copper samples against the total number of irradiated gamma-ray quanta. In order to eliminate the effect of self-absorption of positrons of Cu^{62} in the samples, the ratio of activities of samples to those of a monitor sample was plotted as a function of thickness of samples. From this curve we could extrapolate a value which is not suffering from the effect of self-absorption. Total number of gamma-ray quanta concerned was measured with a Geiger-Mueller counter of thick lead wall, of which counting efficiency was computed theoretically. After measurements of the decay constant of Cu^{62} and of various factors concerning the geometrical arrangement and analysis of the experimental data, the cross section of $Cu^{63}(\gamma, n)Cu^{62}$ for 17.6 Mev $h\nu$ was obtained as $7.7_5 \times 10^{-26}\,\mathrm{cm}^2 \pm 15\%$, which, however, was increased then to $8.5 \times 10^{-26}\,\mathrm{cm}^2 \pm 15\%$ by taking into account the fact that the lithium gamma-rays have a line at 14.8 Mev besides a line at 17.6 Mev. The discussions on the value obtained by other workers are also given.

I. Introduction

Since 1937, studies of photo-neutron effect of 17 Mev and 12 Mev gamma-rays on heavier elements have been made by several investigators[1].

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* Preliminary report was read at the 4th annual meeting of the Physical Society of Japan at University of Tokyo (April 27, 1949).

1. W. Bothe and W. Gentner, Zeits. f. Physik **106** (1937), 236; **112** (1939), 45; W. Y. Chang, M. Goldhaber, and R. Sagane, Nature **139** (1937), 962; P. R. Carlson and J. E. Henderson, Phys. Rev. **58** (1940), 193; O. Huber, O. Lienhard, P. Scherrer, and H. Wäffler, Phys. Rev. **60** (1941), 910; Helv. Phys. Acta **15** (1942), 312; **16** (1943), 33; **18** (1945), 221; O. Huber, O. Lienhard, and H. Wäffler, Helv. Phys. Acta **16** (1943), 226; **17** (1944), 195.

With another type of photo-nuclear reactions[2] the said effects have been carefully studied by us in these ten years. We have been able to confirm the occurrence of (γ, n) reaction produced by 17 Mev gamma-rays which results in the induced activities in some irradiated samples, while, in spite of careful experiments, we could not ascertain the occurrence of this reaction with 6.1 Mev gamma-rays of F (p, γ). The latter fact may be expected from the knowledge that the average binding energy of a neutron in middle-weight nuclei is generally about 8 Mev and more. In the meanwhile, the researchers in Zürich[3] observed the photo-disintegration of (γ, p) type of several elements with the irradiation of 17 Mev gamma-rays. On the other hand, in the United States of America the production of high energy X-rays by betatrons and synchrotrons was achieved and several types of photo-induced nuclear reactions were observed[4]. Baldwin and Koch[5] measured the thresholds of (γ, n) reactions by using the high voltage X-rays from the 20 Mev betatron. Perlman and Friedlander[6] used the X-rays from the 100 Mev betatron and the 80 Mev synchrotron to induce (γ, n), (γ, p), $(\gamma, 2n)$ and $(\gamma, 2p)$ reactions of several nuclei and determined the relative yields for a number of these reactions. Baldwin and Klaiber[7] measured the yield curves for the reactions $C^{12}(\gamma, n)C^{11}$ and $Cu^{63}(\gamma, n)Cu^{62}$ with X-rays up to 100 Mev and found that the relative cross section has a maximum at about 22 Mev for Cu^{63} and 30 Mev for C^{12} while it decreases to negligible value at high quantum energies. Recently, McElhinney *et al.*[8] have estimated approximate cross sections of tantalum and copper for the X-rays from the 22 Mev betatron. In those experiments, however, knowledges of the spectral distribution of the intensity in X-radia-

2. B. Arakatsu, Y. Uemura, M. Sonoda, S. Shimizu, K. Kimura, and K. Muraoka, Proc. Phys.-Math. Soc., Japan **23** (1941), 440; B. Arakatsu, M. Sonoda, Y. Uemura, and S. Shimizu, Proc. Phys.-Math. Soc., Japan **23** (1941), 633; B. Arakatsu, M. Sonoda, Y. Uemura, S. Shimizu, and K. Kimura, Proc. Phys.-Math. Soc., Japan **25** (1943), 173; B. Arakatsu, S. Shimizu, T. Hanatani, and J. Muto, Journ. Phys. Soc., Japan **1** (1946), 24.

3. O. Huber, O. Lienhard, P. Scherrer, and H. Wäffler, Helv. Phys. Acta **16** (1943), 431; **17** (1944), 139; O. Hirzel and H. Wäffler, Ibid. **19** (1946), 214; **20** (1947), 373.

4. G. C. Baldwin and G. S. Klaiber, Phys. Rev. **70** (1946), 259 & 586; **71** (1947), 3; **73** (1948), 1156; J. L. Lawson and M. L. Perlman, 74 (1948), 1190; D. L. Mock, R. C. Waddel, L. W. Fagg, and R. A. Tobin, Phys. Rev. 74 (1948), 1536; M. L. Perlman, Phys. Rev. **75** (1949), 988.

5. G. C. Baldwin and H. W. Koch, Phys. Rev. **67** (1945), 1.

6. M. L. Perlman and G. Friedlander, Phys. Rev. **74** (1948), 442.

7. G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73** (1948), 1156.

8. J. McElhinney, A. O. Hanson, R. A. Becker, R. B. Duffield, and B. C. Diven, Phys. Rev. **75** (1949), 542.

tion from the targets of the betatron or the synchrotron, though it is theoretically predicted, are yet insufficient to make the accurate determination of the absolute cross sections for the photo-disintegration reactions induced by these high voltage X-rays. For the theoretical interest, therefore, it is preferable to make an accurate experiment with monochromatic gamma-rays. Since the (γ, n) reaction of copper for high energy gamma-rays is comparatively strong and the measurements of (γ, n) yield values of various other nuclei have generally been done by taking the value of $Cu^{63}(\gamma, n)\ Cu^{62}$ yield as standard, the measurement of the absolute cross section of this reaction is particularly important. Notwithstanding, there are very few experiments with monochromatic radiation. In 1937, the rough measurement on the cross section of $Cu^{63}(\gamma, n)\ Cu^{62}$ reaction for gamma-rays of $Li\,(p, \gamma)$ was made by Bothe and Gentner,[9] while a measurement has recently been made by Wäffler and Hirzel[10] with the same gamma-rays and a value about three times as large as that of Bothe and Gentner has been obtained.

In the present experiment the absolute cross section of $Cu^{63}(\gamma, n)\ Cu^{62}$ reaction for the 17.6 Mev gamma-rays of $Li\,(p, \gamma)$ reaction has been determined experimentally as carefully as possible, and we have obtained the result that $\sigma_{Cu(17)} = 8.5 \times 10^{-26}\,cm^2 \pm 15\,\%$.

II. Apparatus

For the production of 17.6 Mev gamma-rays we used a high voltage machine of Cockcroft-Walton type equipped in our laboratory. The proton beam of about 460 Kev was directed on the target of thin metallic lithium placed on the bottom of a thin brass tube of 0.2 mm thickness. It was focused to a spot of about 1.5 mm in diameter.

As it is well experienced in our laboratory, the number of gamma-ray quanta was counted by a specially constructed Geiger-Mueller counter with a lead wall of 6.5 mm thickness, the inside diameter and the effective length of which are 2 cm and 2 cm respectively. It was filled with argon of 9 cm Hg mixed with ethyl alcohol of 1 cm Hg. The lead wall of 6.5 mm thickness is able to prevent those electrons from entering into the counter which may be expelled from the surrounding materials exposed to the gamma-rays of $Li\,(p, \gamma)$. The counting efficiency of this lead counter for 17.6 Mev quantum, ε_{ff}, was computed theoretically by

9. W. Bothe and W. Gentner, Zeits. f. Physik **106** (1937), 236.
10. H. Wäffler and O. Hirzel, Helv. Phys. Acta **21** (1948), 200.

M. Sonoda[11] by taking into account the knowledges of Compton effect, electron-pair creation and the effect of multiple scattering and bremsstrahlung of the secondary electrons in the counter wall etc. His result is

$$\varepsilon_{ff} = 0.21_7 \quad \text{for the gamma-ray quantum of 17.6 Mev.}$$

Since in the present stage of our knowledges the rigorous determination of the counting efficiency by accurate experiments is yet difficult, the above theoretical value was presumably used in the computation for determination of the absolute number of gamma-ray quanta concerned. The pulses from the lead counter, after amplification, were counted by a system of scale-of-ten devised by R. Ishiwari and K. Yuasa.[12] In actual measurements the lead counter was placed at a point 29.4 cm apart from the Li-target and was usually shielded by a lead cylinder of 1.05 cm thickness. The practical absorption coefficient of this lead cylinder covering the counter was measured as μ_γ (Pb cylinder) $= 0.53\ \text{cm}^{-1}$. By adopting the above figures of ε_{ff} and μ_γ the actual readings of the counter were corrected in computating the absolute number of gamma-ray quanta concerned; namely, from the net counts, n_γ, the absolute number of gamma-ray quanta emitted from the Li-target, N_γ, is given by the formula:

$$N_\gamma \frac{\omega}{4\pi} \varepsilon_{ff} \exp(-\mu_\gamma x) = n_\gamma\,, \qquad (1)$$

where ω is the solid angle subtended by the effective space of the counter at the target, and x is the thickness of wall of the lead cylinder covering the counter. In the present geometry ω is given by $2 \times 3.3/29.4^2$ steradians and $x = 1.05$ cm.

The samples irradiated were a number of copper (c. p. grade) circular discs. The diameter of all the discs was precisely equal to 22.8 mm, while the thickness was varied from 40.8_1 mg/cm^2 to 1761.9_8 mg/cm^2 as listed in Table I. The effect of irregularity of activation due to the fluctuation of emission of irradiating gamma-rays was corrected by the usage of copper activation monitors of 40 mm in diameter and 801.3_2 mg/cm^2 in thickness.

For the measurement of positron activities induced in these copper samples two Geiger-Mueller counters of end-window type were constructed, of which structural details are shown in Fig. 1. The inside

11. M. Sonoda, Journ. Phys. Soc., Japan, now in press.
12. R. Ishiwari and K. Yuasa, Mem. Coll. Sci. Univ. of Kyoto **25** (1950), 155.

TABLE I. Thickness of copper samples.

Sample No.	Thickness in mg/cm²	
1	40.8_1	diameter = 22.8 mm.
2	54.9_4	
3	82.9_4	
4	120.9_6	
5	271.5_3	
6	523.5_1	
7	858.6_5	
8	1369.9_9	
9	1761.9_8	
Monitor sample	801.3_2	diameter = 40.0 mm.

diameter is 34 mm and the interval between the effective space of the counter and the mica window of 26 mm in diameter is about 6 mm. Each counter was filled with argon of 9 cm Hg mixed ethyl alcohol of 1 cm Hg. One was used for the measurements of activities of samples and the other was used for those of monitors. These two counters have the same dimensions except that the thickness of mica window of the sample counter is 3.7_9 mg/cm² while that of the monitor counter is 6.1_3 mg/cm². Pulses of each counter, after amplification, were fed to a scale-of-four recording circuit of Higinbotham type[13] with a mechanical recorder respectively. Counting measurements with these beta-counters were carefully corrected for counter sensitivity, for geometrical conditions of the arrangement of samples and for absorption in a mica window as described in the following section.

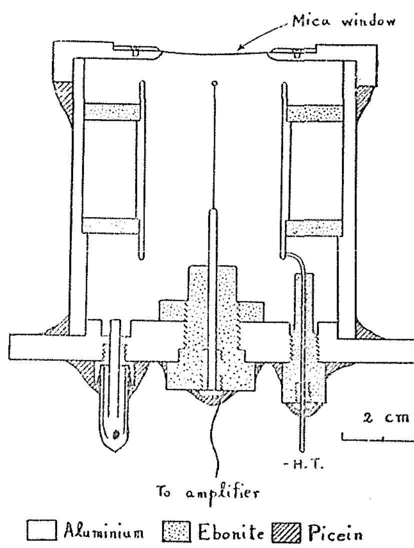

Fig. 1. Beta-ray Geiger-Mueller counter of end-window type.

13. W. A. Higinbotham, J. Gallager, and M. Sands, Rev. Sci. Inst. **18** (1947), 706.

III. Experimental Procedures

A set of sample and monitor, which were fitted closely each other, was mounted, as is shown in Fig. 2, on a plastic circular plate and placed in a definite orientation in the standard geometrical condition of irradiation. The upper surface of a monitor was directly fitted under the bottom of the target tube in such a manner as the axis of proton beam passed through the centers of both monitor and sample.

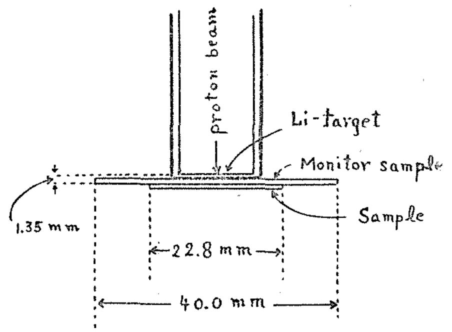

Fig. 2. Standard geometry of irradiation of samples.

The lower surface of the monitor, which was faced immediately to the upper surface of the sample, was laid 1.3_5 mm apart from the point regarded as the gamma-ray source on the Li-target. After the irradiation for several minutes both sample and monitor were transferred to the definite positions respectively, where the lower surface of monitor was faced to the mica window of the monitor counter separating 2.0 mm while the upper surface of the sample was faced to the window of the sample counter separating 1.7 mm. During the lapse of one minute, after the end of irradiation, the mentioned measurement condition was realized for each run of experiments by using the device having the delicately adjustable screws. In this standard geometry, the counting measurements of induced activities produced respectively in sample and monitor were begun simultaneously at just one minute after the end of irradiation and were continued for the following 10 minutes. Such measurements for each of samples of different thickness were carried out.

The results obtained are plotted in Fig. 3, in which N_s/N_m is given in a dotted curve and $N_s/N_m \cdot w_s$ in a solid curve as a function of thickness of samples respectively, where net counts of the sample counter and those of the monitor counter are denoted by N_s and N_m respectively. The thickness of samples is presented in this case by weight per unit area, w_s, in g/cm^2. We see that the dotted curve tends to saturation as the thickness of samples becomes larger. The aspect may be expected from the fact that the induced beta-rays have the definite maximum energy of about 2.6 Mev corresponding to about 1.4 mm range in copper. The solid curve shows the variation of the value which is proportional

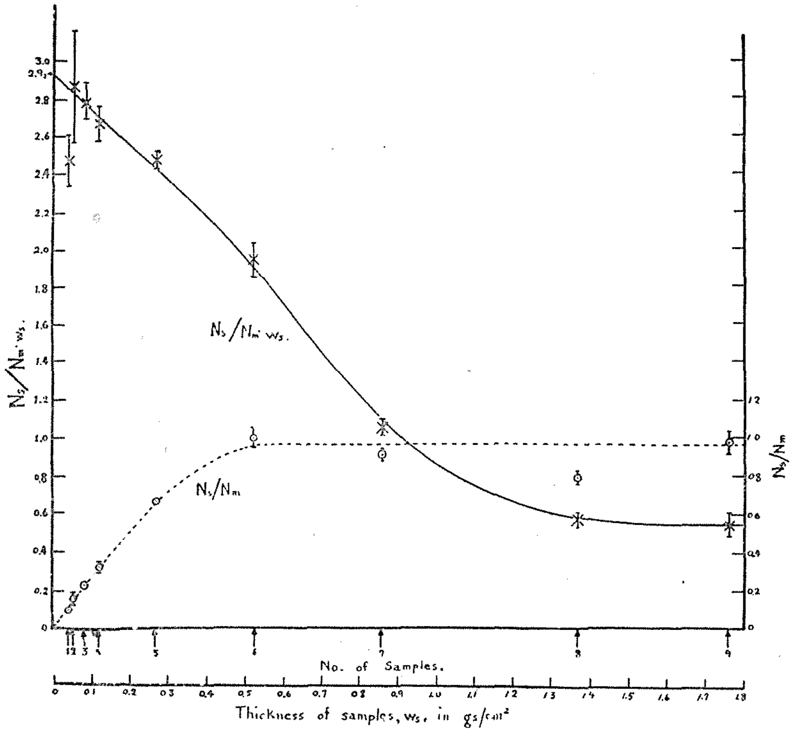

Fig. 3. The ratio of net counts of the sample counter, N_s, to those of the monitor counter, N_m, as a function of the thickness of samples, w_s.

to the apparent activities produced in unit thickness of samples. This curve was extrapolated to zero thickness by taking the weight of measurements into account. By this procedure we obtained a limiting value $\lim_{w_s \to 0} (N_s/N_m \cdot w_s) = 2.9_2$, which is obviously be taken as the value without suffering from the effect of self-absorption of positrons in the samples. However, in order to obtain the absolute number of Cu^{62} produced in a sample, it must be necessary, furthermore, to make the correction for the absorption of beta-rays in a mica window of the counter and that for the effects of the radiative position of the sample and the counter. We need, now, to know how many percent of beta-rays emitted from the surface of a sample may be counted by the sample counter.

By assuming the simple exponential law, the absorption coefficient of mica for positrons of Cu^{62}, μ_β, was determined by inserting a series of thin mica sheets between the sample and the counter, and we have found that $\mu_\beta = 0.0123\,(\text{mg/cm}^2)^{-1}$. The correction factor for the absorption in a mica window of the sample counter was obtained as: $C_\beta = 1.04_7$.

Since the geometrical correction was one of the most important factors for the calculation of the cross section, we determined this value carefully by laborious experiments. As a first step we observed the variation of counts against the varying distance between sample and mica window. It was found that the logarithm of counts decreases linearly with the distance. After a series of separate experiments done on this line we arrived at the conclusion that the geometrical correction, C_g, is 2.1 ± 0.1. And hence the total number of positrons emitted from the whole surface of the sample, N_β, is given by

$$N_\beta = 2C_g C_\beta N, \qquad (2)$$

where N is the net counts of the counter.

The mean life, τ, or decay constant, λ, of Cu^{62}, which is inevitably necessary for calculation of the cross section, was determined by the counting data obtained throughout the course of the present experiment by applying the rigorous theoretical treatment of Peierls.[14] The result obtained was $\tau = 15.2_1 \pm 0.4$ min. or $\lambda = 1/\tau = 0.0657 \pm 0.0017 \text{ min}^{-1}$.

In practice, moreover, we ascertained that the effect of annihilation radiation of positrons upon the counting data was almost negligibly small by observing that the counts due to activities of the sample were reduced to natural counts of the counter when about 3 mm thick copper plate was inserted between the counter and the sample.

During the experiment the number of grmma-ray quanta was measured for the time interval of each half minute continuing 8 minutes necessitated for the irradiation.

IV. Calculation of Reaction Cross Section

When the irradiation of gamma-rays is made in the geometry shown in Fig. 4, in which a disc sample of radius r_0 and thickness δ is placed apart a from the gamma-ray point source, $(a < r_0)$, the number of active nuclei, dA, produced in an infinitesimal time interval, $(t, t + dt)$, can be written in a form:

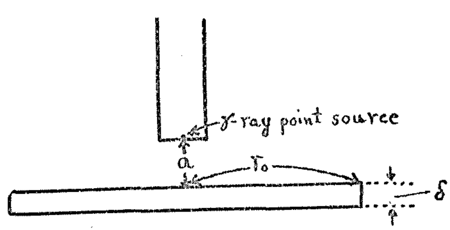

Fig. 4. A geometry of irradiation: a circular disc sample is placed closely under the gamma-ray point source.

$$dA = \sigma m N_\gamma \left[\frac{1}{4} \int_a^{a+\delta} \log\left(\frac{a^2 + r_0^2}{a^2} \right) da \right] dt, \qquad (3)$$

14. R. Peierls, Proc. Roy. Soc., A, **149** (1935), 467.

where

σ = reaction cross section for $Cu^{63}(\gamma, n)\, Cu^{62}$,

m = number of Cu^{63} atoms per cc in copper sample,

N_γ = total number of 17.6 Mev quanta emitted from the Li-target per unit time.

If the irradiation continues for T minutes with constant intensity, the number of active nuclei produced, A, is given by

$$A = \int_{t=0}^{T} \exp\Big[-\lambda(T-t)\Big] dA$$

$$= \int_0^T \sigma m N_\gamma \left[\frac{1}{4}\int_a^{a+\delta} \log\left(\frac{a^2+r_0^2}{a^2}\right) da\right] \exp\Big[-\lambda(T-t)\Big] dt$$

$$= \frac{\sigma m N_\gamma}{4\lambda}\left[\int_a^{a+\delta} \log\left(\frac{a^2+r_0^2}{a^2}\right) da\right]\Big[1-\exp(-\lambda T)\Big], \qquad (4)$$

where λ is the decay constant of Cu^{62} in min^{-1}. Since, in practice, as described in the preceding section, the sample was irradiated during 8 minutes and for each half minute of which gamma-ray counts were recorded, the number of Cu^{62} atoms existed at the time when the measurement of activities was commenced—one minute after the end of irradiation—can be given by

$$A_0 = \frac{\sigma m}{4\lambda}\left[\int_a^{a+\delta} \log\left(\frac{a^2+r_0^2}{a^2}\right) da\right]\Big[1-\exp(-0.5\lambda)\Big]$$

$$\times \sum_{i=1}^{16} 2N_{\gamma_i} \exp\Big[-\lambda(9-0.5i)\Big], \qquad (5)$$

where N_{γ_i}'s are the total number of gamma-ray quanta emitted from the target during each half minute interval in 8 minutes of the irradiation. Since, according to Eq. (1), the net counts of the gamma-ray counter, n_{γ_i}, are related with N_{γ_i} as

$$N_{\gamma_i} \frac{\omega}{4\pi} \epsilon_{ff} \exp(-\mu_\gamma x) = n_{\gamma_i}, \qquad (6)$$

and the number of Cu^{62} atoms that disintegrate in the following 10 minutes, A_d, can be expressed by, using Eqs. (5) and (6),

$$A_d = A_0\Big[1-\exp(-10\lambda)\Big]$$

$$= \frac{\sigma m \pi}{\omega\, \epsilon_{ff}\, \lambda \exp(-\mu_\gamma x)}\left[\int_a^{a+\delta} \log\left(\frac{a^2+r_0^2}{a^2}\right) da\right] \times$$

$$\times \Big[1 - \exp(-0.5\lambda)\Big]\Big[1 - \exp(-10\lambda)\Big]$$

$$\times \sum_{i=1}^{16} 2 n_{\gamma_i} \exp\Big[-\lambda(9 - 0.5 i)\Big]. \qquad (7)$$

Now, the observed counts for sample, N_s, and those for monitor sample N_m, are given by, according to Eqs. (2) and (7),

$$\left.\begin{aligned} N_s &= \left[\frac{A_a\, K}{2\, C_g C_\beta}\right]_s = \left[\frac{K\displaystyle\int_a^{a+\delta} \log\left(\frac{a^2 + r_0^2}{a^2}\right) da}{2\, C_g C_\beta}\right]_s \times P, \\ N_m &= \left[\frac{A_a\, K}{2\, C_g C_\beta}\right]_m = \left[\frac{K\displaystyle\int_a^{a+\delta} \log\left(\frac{a^2 + r_0^2}{a^2}\right) da}{2\, C_g C_\beta}\right]_m \times P, \end{aligned}\right\} \qquad (8)$$

where K is the correction factor for self-absorption and, referring to Eq. (7), a common factor, P, is given by

$$P = \frac{\sigma m \pi}{\omega\, \varepsilon_{ff}\, \lambda \exp(-\mu_\gamma x)} \Big[1 - \exp(-0.5\lambda)\Big]$$

$$\times \Big[1 - \exp(-10\lambda)\Big] \sum_{i=1}^{16} 2 n_{\gamma_i} \exp\Big[-\lambda(9 - 0.5 i)\Big]. \qquad (9)$$

And the suffixes s and m mean that the notations contained in each bracket are concerned in the sample and the monitor respectively. From the expressions (8) we obtain

$$\frac{N_s}{N_m\, w_s} = \frac{N_s}{N_m\, \rho\, \delta_s} = \frac{P}{N_m\, \rho\, \delta_s}\left[\frac{K\displaystyle\int_a^{a+\delta} \log\left(\frac{a^2 + r_0^2}{a^2}\right) da}{2\, C_g C_\beta}\right]_s, \qquad (10)$$

where ρ is density of the sample.

Now, when $w_s \to 0$ or $\delta_s \to 0$,

$$\left.\begin{aligned} &K_s \to 1, \\ &\left[\frac{1}{\delta}\int_a^{a+\delta} \log\left(\frac{a^2 + r_0^2}{a^2}\right) da\right]_s \to \left[\log\left(\frac{a^2 + r_0^2}{a^2}\right)\right]_s. \end{aligned}\right\}.$$

Applying these relations to Eq. (10) we obtain at once

$$Q \equiv \lim_{w_s \to 0} \frac{N_s}{N_m\, w_s} = \lim_{\delta s \to 0} \frac{N_s}{N_m\, \rho\, \delta_s} = \frac{P}{N_m\, \rho}\left[\frac{\log\left(\dfrac{a^2 + r_0^2}{a^2}\right)}{2\, C_g C_\beta}\right]_s. \qquad (11)$$

The value of Q is obtained experimentally as described in the preceding section.

Using Eqs. (9) and (11) we get the final expression of σ:

$$\sigma = \frac{2N_m\,\rho[C_g]_s[C_\beta]_s\,Q\,\omega\,\varepsilon_{ff}\,\lambda\exp(-\mu_\gamma x)}{m\pi\left[\log\left(\frac{a^2+r_0^2}{a^2}\right)\right]_s\left[1-\exp(-0.5\lambda)\right]\left[1-\exp(-10\lambda)\right]}$$

$$\times\frac{1}{\sum_{i=1}^{16} 2n_{\gamma_i}\exp\left[-\lambda(9-0.5i)\right]}. \qquad (12)$$

It is to be noticed that this expression contains no counting data concerning the samples but those of the monitor used simultaneously with the samples. Thereby we have the advantage of employing the counts of the monitor which are less suffering from the statistical errors than those of samples.

Numerical computation of Eq. (12) has been done by employing the values obtained by the present experiment as follows:

λ = decay constant of Cu^{62} = $0.0657 \pm 0.0017\ \mathrm{min}^{-1}$,

$[C_g]_s$ = correction factor concerning the geometrical conditions of activity measurement of sample = 2.1 ± 0.1,

$[C_\beta]_s$ = correction factor for the absorption of positrons of Cu^{62} from the sample in a mica window of the counter $=1.04_7$,

ε_{ff} = counting efficiency of the gamma-ray counter for 17.6 Mev $h\nu = 0.21_7$,

ω = solid angle subtended by effective space of the gamma-ray counter at the gamma-ray source = $2\times 3.3/29.4^2$ steradians,

μ_γ = practical absorption coefficient of the lead cylinder covering the gamma-ray counter for the gamma-rays of Li (p, γ) = $0.53\ \mathrm{cm}^{-1}$,

x = wall thickness of the lead cylinder covering the gamma-ray counter = 1.05 cm,

m = number of Cu^{63} atoms per cc in copper sample = (Avogadro's number × abandance ratio* of Cu^{63} × density of copper, ρ.)/atomic weight of normal copper = $6.48_6 \times 10^{21} \times \rho$,

* The value of abundance ratio of Cu^{63} used here is 68 % (J. Mattauch, *Kernphysikalische Tabellen*, Springer-Verlag, Berlin, 1942).

$[a]_s$ = distance between the sample and the gamma-ray source = 1.3_5 mm,

$[r_0]_s$ = radius of the sample = 11.4 mm,

$Q = \lim_{w_s \to 0} (N_s/N_m \cdot w_s) = 2.9_2$,

N_m = observed net counts of the activities of the monitor (summation from 6 runs), as shown in Table II,

$n_{\gamma i}$ = observed net counts of the gamma-ray counter for each half minute interval in 8 minutes of the irradiation (summation from 6 runs), as shown in Table II.

Thus we have obtained the result that $\sigma = 7.7_5 \times 10^{-26}\,\mathrm{cm}^2$ with a probable error of about 15 percent.

TABLE II. Experimental data

n_{γ_i}								
Run No. \ i	1	2	3	4	5	6	7	8
1	244	304	408	368	348	364	332	376
2	324	364	324	324	344	292	272	260
3	192	394	368	352	304	284	260	272
4	256	356	392	368	288	336	296	268
5	256	324	312	160	268	296	328	284
6	252	336	308	316	288	296	244	248
Total	1524	2080	2112	1888	1840	1868	1732	1708
Natural counts	43.8	43.8	43.8	43.8	43.8	43.8	43.8	43.8
$n_{\gamma i}$	1480.2	2036.2	2068.2	1844.2	1796.2	1824.2	1688.2	1664.2
$\exp[-\lambda(9-0.5i)]$*	0.5718	0.5910	0.6108	0.6313	0.6525	0.6740	0.6963	0.7196
$n_{\gamma i}\exp[-\lambda(9-0.5i)]$	846.38	1203.39	1263.26	1164.24	1172.02	1129.51	1175.49	1197.56
$\sum_{i=1}^{16} 2n_{\gamma i}\exp[-\lambda(9-0.5i)]$								

* $\lambda = 0.0657 \pm 0.0017\ \mathrm{min}^{-1}$.

V. Results and Discussions

In the present experiment a new method of eliminating the effect of self-absorption of beta-rays induced in the sample was introduced and various careful experiments for determining many important and necessary factors have been carried out. The cross section of Cu^{63} (γ, n) Cu^{62} has been then found to be

$$\sigma_{Cu(17)} = 7.7_5 \times 10^{-26}\ \mathrm{cm}^2 \pm 15\ \%\ \text{ for } 17.6\ \mathrm{Mev}\ h\nu \text{ of } \mathrm{Li}\,(p, \gamma)\,.$$

This result, however, has been obtained on the assumption that the gamma-rays of Li (p, γ) constitute themselves of the quanta of 17.6 Mev monochromatically. But, according to the determination of energy of the radiation by several workers such as Delsasoo, Fowler and Lauritsen[15] and Walker and McDaniel,[16] there are probably two lines instead of a single line, namely, one line at 17.6 Mev and another at 14.8 Mev. And the ratio of intensities of the lower energy line to the higher energy line was found to be approximately 0.5_0 for the protons

of $n_{\gamma i}$ and N_m.

9	10	11	12	13	14	15	16	N_m
328	284	316	344	308	296	312	292	1273
260	280	248	252	248	252	252	236	1042
204	204	232	256	240	252	224	228	1070
260	212	260	236	216	232	216	235	1107
260	228	224	180	232	208	200	203	1091
232	224	220	204	224	200	228	200	1082
1544	1432	1500	1472	1468	1440	1432	1394	6665
43.8	43.8	43.8	43.8	43.8	43.8	43.8	43.8	1725.9
1500.2	1388.2	1456.2	1428.2	1424.2	1396.2	1388.2	1350.2	
0.7438	0.7687	0.7945	0.8212	0.8487	0.8767	0.9057	0.9361	$N_m = 4939.1$
1115.85	1067.11	1156.95	1172.84	1208.72	1224.05	1257.29	1263.92	
= 37437.36								

of 460 Kev bombarding energy.

Therefore the value of $\sigma_{Cu(17)}$ obtained from this experiment should

15. L. A. Delsasoo, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **51** (1937), 391.
16. R. L. Walker and B. D. McDaniel, Phys. Rev. **74** (1948), 315.

be increased by a factor, α, which is given by

$$\alpha = \left(1 + \frac{\varepsilon_{14}}{\varepsilon_{17}} R\right) \Big/ \left(1 + \frac{\sigma_{Cu(14)}}{\sigma_{Cu(17)}} R\right),$$

where R is the ratio of intensities of the line at 14.8 Mev to that at 17.6 Mev, and ε_{17} and ε_{14} are the counting efficiencies of the gamma-ray counter for each of the components of the rays respectively, and are given by M. Sonoda[11] as $\varepsilon_{17} = 0.21_7$ and $\varepsilon_{14} = 0.17_2$ respectively. According to the theory of Weisskopf[17] the cross section is proportional to $(h\nu)^3$, so the ratio of cross sections for 14.8 Mev $h\nu$ and 17.6 Mev $h\nu$, $\sigma_{Cu(14)}/\sigma_{Cu(17)}$, is considered to be $(14.8/17.6)^3 = 0.595$. Recently, by the measurements with high voltage X-rays, however, the ratio is given as about 0.61 by McElhinney *et al.*[8] and as about 0.17 by Baldwin and Klaiber.[7] If R is taken to be 0.5, α's should be given from the above relation, according as the three different values of $\sigma_{cu(14)}/\sigma_{cu(17)}$, as

$$\alpha = \begin{cases} 1.07_6 \text{ for } \sigma_{Cu(14)}/\sigma_{Cu(17)} = (14.8/17.6)^3 = 0.595, \\ 1.07_1 \text{ for } \sigma_{Cu(14)}/\sigma_{Cu(17)} = 0.61, \\ 1.28_8 \text{ for } \sigma_{Cu(14)}/\sigma_{Cu(17)} = 0.17. \end{cases}$$

Then the corrected values of the cross section of the reaction under consideration are given as

$$\sigma_{cu(17)} = \begin{cases} 8.3_5 \times 10^{-26}\,\text{cm}^2 \text{ for } \alpha = 1.07_6, \\ 8.3_0 \times 10^{-26}\,\text{cm}^2 \text{ for } \alpha = 1.07_1, \\ 9.9_8 \times 10^{-26}\,\text{cm}^2 \text{ for } \alpha = 1.28_8, \end{cases}$$

respectively. Since, however, the theory of Weisskopf is based on several assumptions and is not yet complete while the measurements of the relative yield of these reactions carried with X-rays from betatrons involve several uncertainties because of the lack of the accurate knowledge of the spectral distribution of quanta in them, the value $\sigma_{Cu(14)}/\sigma_{Cu(17)}$ is fairly ambiguous. Though, therefore, we can not ascertain which of these three different values is most reliable, we may yet conclude that $\sigma_{Cu(17)}$ lies between 7.2×10^{-26} cm^2 and 10.8×10^{-26} cm^2 as is shown in Fig. 5, in which $\sigma_{Cu(17)}$ is given as a function of $\sigma_{Cu(14)}/\sigma_{Cu(17)}$.

In this way, we arrive at the conclusion that the cross section of $Cu^{63}(\gamma, n)Cu^{62}$ is to be taken as

$$\sigma_{Cu(17)} = 8.5 \times 10^{-26}\,\text{cm}^2 \pm 15\,\% \text{ for } 17.6\text{ Mev } h\nu.$$

17. V. F. Weisskopf, Phys. Rev. **59** (1941), 318.

However, if the ratio of cross sections for 14.8 Mev $h\nu$ and 17.6 Mev $h\nu$ is precisely determined, one can easily find a more accurate value of $\sigma_{Cu(17)}$ by inspecting the curve shown in Fig. 5.

The historical value of Bothe and Gentner[9] obtained in 1937, 5×10^{-26} cm^2, may be considered to be too small, since the contribution of 14.8 Mev $h\nu$ on the reaction was neglected in their measurements.

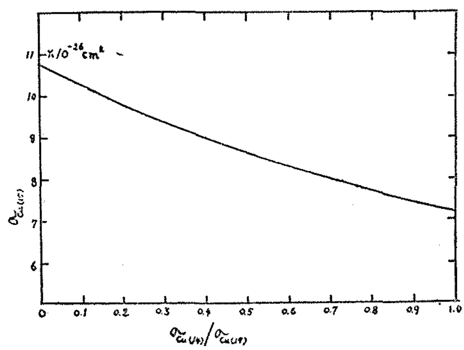

Fig. 5.

$\sigma_{Cu(17)}$ as a function of $\sigma_{Cu(14)}/\sigma_{Cu(17)}$. This curve is given by

$$7.7_5 \times \frac{1+\frac{\varepsilon_{14}}{\varepsilon_{27}}R}{1+\frac{\sigma_{Cu(14)}}{\sigma_{Cu(17)}}R} \times 10^{-26}\,\mathrm{cm}^2,$$

where $\varepsilon_{17} = 0.21_7$, $\varepsilon_{14} = 0.17_2$, and $R = 0.5_0$.

Recent measurements by Wäffler and Hirzel[10] gave a value of 12×10^{-26} cm^2. This value was obtained from the experiments with the gamma-rays of Li (p, γ) and was corrected to 16×10^{-26} cm^2 by taking into account the existence of 14.8 Mev line. However, as it is discussed above, this value may be presumably too large.

Since the energy levels of heavier nuclei are not precisely determined, there is, so far, no theoretical way to calculate the cross section. Notwithstanding, under some simplified assumptions Weisskopf[17] calculated that the cross section is proportional to $(h\nu)^3$, and he obtained the proportionality constant from the measurements of Bothe and Gentner[18] of relative yields of (γ, n) reactions for the gamma-rays produced by Li (p, γ) and B (p, γ) reactions. According to his theory the cross section is expected to be about 3.5×10^{-26} cm^2 or less. On the other hand, the behavior of resonance phenomena of (γ, n) reactions was observed for the high voltage X-rays. Baldwin and Klaiber[7] observed such a resonance in carbon at 30 Mev and in copper at 22 Mev. A theory to account for this phenomenon has been put forward by Goldhaber and Teller[19] in analogy with the " reststrahl frequencies " of polar crystals. According to their theory $h \int \sigma d\nu$ for copper is predicated as about 1 Mev-barn,

18. W. Bothe and W. Gentner, Zeits f. Physik **112** (1939), 45.
19. M. Goldhaber and E. Teller, Phys. Rev. **74** (1948), 1046.

which corresponds to $\sigma_{Cu(17)} = 5 \times 10^{-26}\,cm^2$. Lawson and Perlman[20] have recently measured $h \int \sigma d\nu$ for $C^{12}(\gamma, n)C^{11}$ by using the 50 and 98 Mev X-rays, and deduced the value of $h \int \sigma d\nu$ for $Cu^{63}(\gamma, n)Cu^{62}$ as 1.5 Mev-barns which means that $\sigma_{cu(17)}$ is about $7.5 \times 10^{-26}\,cm^2$.

Another value of $\sigma_{Cu(17)}$ has been reported by McElhinney *et al*[8]., to be about $6.7 \times 10^{-26}\,cm^2$. On the other hand, $Cu^{63}(e; n, e')Cu^{62}$ was studied by Skaggs *et al.*[21] by bombarding electrons of 22 Mev directly upon the target. They obtained the electro-disintegration cross section of this reaction for 17.5 Mev electron as $32 \times 10^{-29}\,cm^2$, from which the photo-disintegration cross section is expected to be about $13 \times 10^{-26}\,cm^2$ by taking the cross section for photo-disintegration by $h\nu$ above threshold energy approximately 400 times that for electro-disintegration.

As mentioned above the values obtained from betatron experiments are considered in general to be rather in large error, and values given so far by several workers differ to a great extent. In the present state of knowledges the value $8.5 \times 10^{-26}\,cm^2$ obtained by the present experiment is, then, considered to be most close to the fact, nevertheless we have a prospect of obtaining a more accurate value when the ratio of cross sections for 14.8 Mev $h\nu$ and 17.6 Mev $h\nu$ would be precisely measured as described in this discussion.

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20. J. L. Lawson and M. L. Perlman, Phys. Rev. **74** (1948), 1190.
21. L. S. Skaggs, J. K. Laughlin, A. O. Hanson, and J. J. Orlin, Phys. Rev. **73** (1948), 420.