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ABSOLUTE MEASUREMENT OF γ-QUANTA

BY

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ABSTRACT

Absolute measurement of γ-quanta from the Li-p reaction was performed by Hough's method. By using this result, the efficiency of the γ-monitor was calibrated and the Pb thick-walled G-M counter was also calibrated which was previously used in our laboratory.

Discussions are given on the determination of the absolute number of γ-quanta with the previous γ-counter as well as on the absolute cross section values of (γ, n) reactions.

1. Introduction

Up to the present, several measurements on the cross sections of photo-nuclear reaction by Li-p γ-ray have been performed in our laboratory (**1**), in which the absolute number of the γ-ray flux was measured with Pb thick-walled G-M counter (**2**) whose efficiency was calculated theoretically (**3**).

In the present work we determined the absolute number of Li-p γ-ray flux by using Hough's method (**4**), and then calibrated the efficiency of the γ-monitor counter, with which we measured (γ, n) cross sections of Cu^{63}, Zn^{64} and Ag^{109} for Li-p γ-ray. Furthermore, using this result, we evaluated experimentally the efficiency of the Pb thick-walled G-M counter for Li gamma ray (hereafter we shall call this the 'previous γ-counter') and tried to correct the photo-nuclear cross sections obtained by the previous experiments (**1**).

2. Experimental method and apparatus

Hough's method may be summarized as follows: When a thin metal foil is placed in front of a Geiger counter on the passage of γ-rays, the counting rate of the counter will increase due to secondary electrons from metal foil produced by γ-rays. From this excess counting rate and the electronic cross section of γ-ray for a converter material, we can obtain the γ-ray flux at the position of the converter foil. Fig. 1 shows schematic view of the apparatus used in the present measurement.

We can expect that a G-M counter can count almost all the secondary electrons

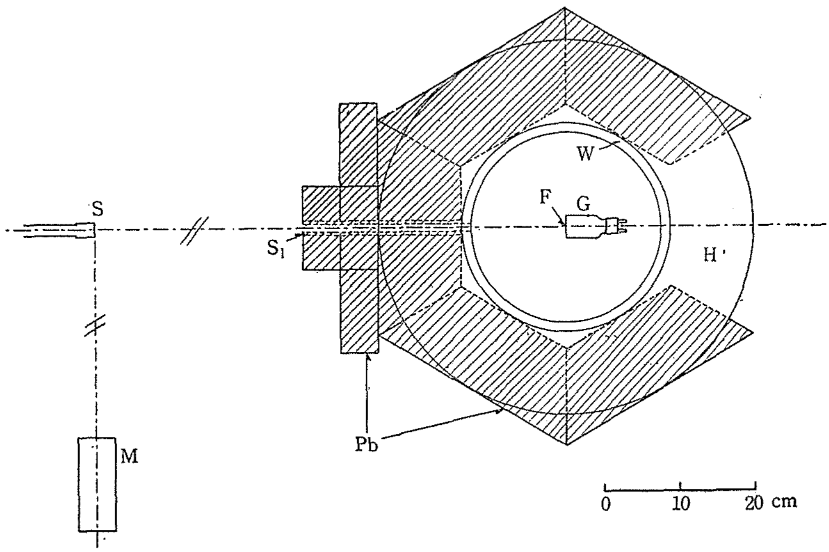

Fig. 1.

G :	GM counter for converting electron	F :	converter foil
S_1 :	γ-ray slit	S :	γ-ray source
Pb :	lead shield for γ-ray	W :	inner shield of wood
H :	Helmholtz coil	M :	monitor counter

produced at Pb converter foil if the latter foil is sufficiently thin and the counter window is also sufficiently thin and wide*.

In this case, the count of the counter is given as follows:

$$N_c(w) = N_{c0} + n_\gamma \frac{A_0}{M} w \bar{\sigma}_e \,, \tag{1}$$

where

$N_c(w)$: count of the counter with Pb foil of w gram,

N_{c0} : count of the counter without Pb foil,

n_γ : number of γ-quanta per cm^2 at the position of the Pb foil,

$\bar{\sigma}_e$: electronic absorption cross section of Pb for Li-p γ-ray (averaged over 17.6 Mev and 14.8 Mev γ-rays),

w : weight of the Pb converter foil (gram),

A_0 : Avogadro number,

M : molecular weight of Pb.

The γ-monitor counter to be calibrated was in operation together with the converter counter, and we measured the ratio of $N_c(w)$ to the count of γ-monitor counter N_M for various weights of the converter. Then, Eq. (1) becomes

$$N_c(w)/N_M = N_{c0}/N_M + (n_\gamma/N_M)(A_0/M) w \bar{\sigma}_e \,. \tag{2}$$

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* For this point, see Appendix,

We used end-window type G–M counters whose mica windows are about 2 mg per cm^2 thick for both the converter counter and a β-counter in the γ-monitor counter. The construction of the latter is shown in Fig. 2.

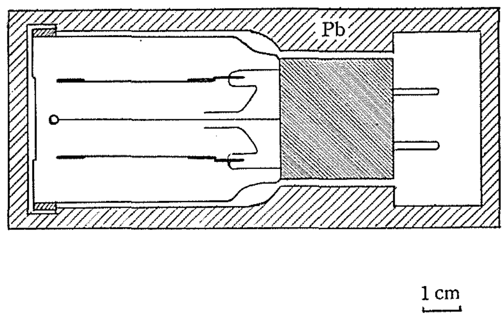

Fig. 2. γ monitor counter.

The ratio N_{c0}/N_M should be as small as possible to ensure the accuracy of measurements. For this purpose special care was taken for arrangements of the apparatus as follows: (1) The dimension of the slit in Fig. 1 was so chosen that the γ-ray flux through it sufficiently covered the converter foil (1 cmϕ) and did not collide the G–M counter wall, (2) Helmholtz coils and Pb blocks were arranged as shown in Fig. 1 and Pb blocks were hollowed at the backward of the counter, (3) the magnetic field of the Helmholtz coils was used to remove secondary electrons from the surrounding materials, the intensity of which was about 1,600$\sim$2,000 gauss at the center of the coils, and so all electrons of energy of about 5 Mev or less were deflected and could not reach the β-counter tube, (4) the inside surface of the shield was covered with wood of 2 cm thick, so that the secondary electrons from it were fewer than Pb (low Z) and also the secondary electrons from the inside surface of the shields were partly absorbed, and (5) the converter was held with 'cello tape' in front of the mica window of the G–M converter counter.

In this experiment, the alignment of γ source-slit-converter-counter system is very important and so we ascertained these alignment in every run by a special jig. The slit of 5 mmϕ was placed just before the Li-target in order to define the position of the γ source as well as possible.

3. Results

The ratio $N_c(w)/N_M$ is plotted against various thicknesses (w=0, 0.1881, 0.2640, 0.3533 and 0.4989 grams) of the converter foils in Fig. 3, in which a solid line is a best fit by the method of least squares using Eq. (2). From this slope of the straight line, we find

$$n_\gamma/N_M = (5.12 \pm 0.62) \times 10^{-1}\,,$$

where we have used $\bar{\sigma}_e = (19.6 \pm 0.12)$ barn as the electronic absorption cross section of Pb for Li–p γ-ray, averaged over 17.6 Mev and 14.8 Mev γ-rays (**5**).

Consequently, the total number of γ-quanta, N_γ, emitted from a target is given as follows for one count of the monitor counter placed at a distance of 31.7 cm from the γ-source:

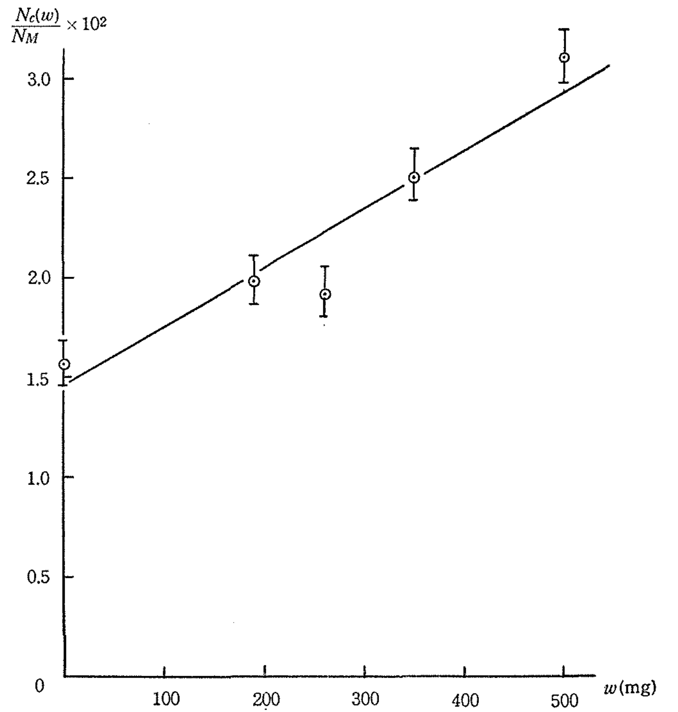

Fig. 3.

$$\frac{N_\gamma}{N_M} = \frac{n_\gamma}{N_M} 4\pi R^2 = (1.63 \pm 0.20) \times 10^4 .$$

We examined the variation of $N_M(d)/N_0$ against d^2, by changing the distance between the γ-monitor counter and the γ-ray source, where N_0 is the count of another fixed γ-monitor counter. This result indicates that the inverse square law holds nearly well.

The error of the result is considered to come from several origins: namely, w, $\bar{\sigma}_c$, R, counting-losses of electrons from the converter foil, the absorption of the γ-ray by the converter foil, and the statistical error of the β-counting. For w, $\bar{\sigma}_c$ and R, each error is one per cent or less respectively and can be neglected. The counting-loss of electrons is negligible for Li-p γ-rays as shown in Appendix. The absorption of γ-ray by the converter foil is about 3 per cent for Pb foil of 500 mg/0.8 cm^2, but the correction for this was not done. After all, the statistical error is the largest source of errors. Thus the errors of the measured values as shown in Fig. 3 are only the statistical ones of the β-counting. The counting stability of each counter was checked in every measurement with constant γ-source placed at the fixed position.

It is an essential defect of Hough's method that some degraded γ-rays may exist among the incident γ-rays at the position of converter foil. For the case of Li-p γ-ray, most of them are produced in the forward direction by Compton scattering, and so we tried to reduce them by using the sloped slit.

Another attention was paid to make use of a fresh Li metal target every day, because the contamination of the carbon on the target produces the C^{12}-p γ-ray. Further, we measured the spectrum of the Li-p γ-ray by a NaI crystal scintillation counter with the dimensions of 5 inch×4 inch immediately after the experiment and it was found that the contamination of C^{12}-p γ-ray was negligibly small throughout the experiment.

4. The cross sections of Cu^{63}, Zn^{64}, Ag^{109} (γ, n) reactions

Using the results for the γ-ray flux thus obtained, we measured the cross sections of Cu^{63}, Zn^{64}, Ag^{109} (γ, n) reactions for Li-p γ-rays.

Li metal targets of thickness of 0.5 mm were bombarded with magnetically analysed protons which were accelarated to 500 Kev by a Cockcroft generator and whose intensities were about 50 μA~100 μA. These γ-rays were irradiated to sample discs made of copper, zinc and silver respectively, and the (γ, n) cross sections of these nuclei were determined by the activation method.

The size of the proton beam spot was about 8 mm in diameter, and the distance between the sample disc and the γ-ray source was 14.5 mm, the former having been fixed on the target box with an aluminium jig as shown in Fig. 4.

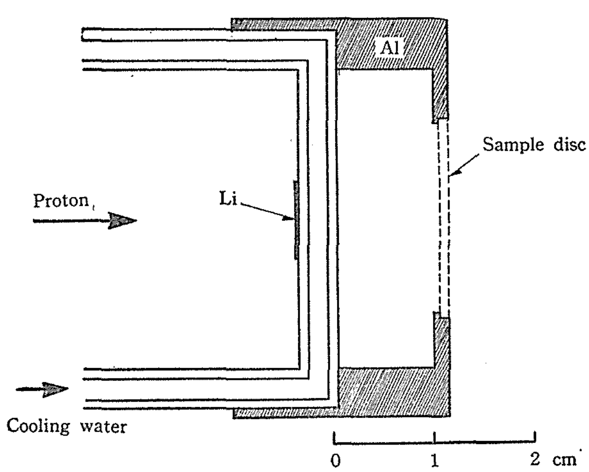

Fig. 4. γ source and sample holder.

The sample discs used are all of diameter of 20 mm, and 1 mm thick for copper and silver and 0.6 mm thick for zinc respectively. These dimensions were the same as the monitor disc's, which had been used by one of the present authors in the measurement of the 14 Mev neutron reaction cross section (**6**). In the β counting we also used the same counting system as that used in the previous measurement by means of the 14 Mev neutron (see Fig. 5).

The cross sections obtained are shown in Table I. In this table λ is decay constant, S is specific activity, C_G is geometrical correction factor and C_k is correction

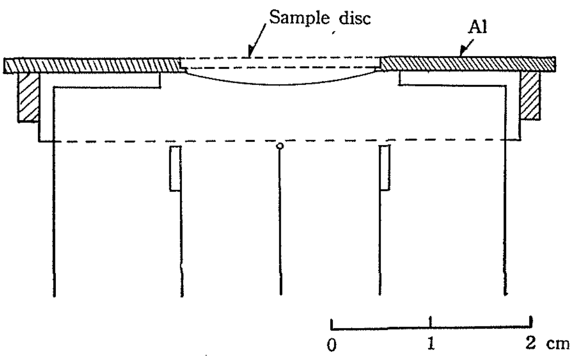

Fig. 5. β counting jig.

factor concerning the branching ratio between the positron emission and the orbital electron capture. The error of the cross section values mainly comes from the error in the determination of γ-ray flux which is about 13%. In the estimation of the cross section by the 17.6 Mev γ-rays only, we adopted Walker and McDaniel's data (5) as the intensity ratio of the 17.6 Mev line to the 14.8 Mev line in the Li-p γ-rays, and used the averaged value of several experimental data by the bremsstrahlung (7) as the (γ, n) cross section ratio of the 17.6 Mev line to 14.8 Mev line: $\sigma(17.6\ \text{Mev})/\sigma(14.8\ \text{Mev})=1.76$.

Table I.

Reaction	λ min^{-1}	S	C_G	C_k	(Li-pγ) mb	(17.6 Mev) mb
$Cu^{63}(\gamma, n)Cu^{62}$	0.0695	2.84$\pm$ 3%	4.79$\pm$2%	1.043	37.7$\pm$15%	42.5
$Zn^{64}(\gamma, n)Zn^{63}$	0.018	3.80$\pm$10%	4.80$\pm$4%	1.075	20.7$\pm$18%	23.3
$Ag^{109}(\gamma, n)Ag^{108}$	0.295	5.03$\pm$ 7%	4.72$\pm$3%	1.00	54.6$\pm$16%	61.5

5. The efficiency of the previous γ-counter

The previous γ-counter which had been used in our laboratory has been constructed to be suitable for high energy γ-ray counting (2). Its construction is shown in Fig. 6. Whenever this counter was used as a γ-monitor, it was shielded by 10.5 mm thick lead and its center wire was placed vertically to γ-rays.

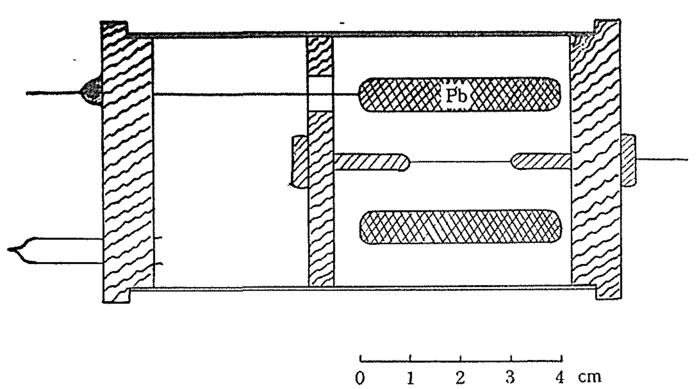

Fig. 6. Reconstructed previous γ counter.

The number of γ-quanta, N_γ, emitted from a target in 4π-steradian has been obtained from the following equation :

$$N_\gamma e^{-\mu x} \frac{a}{4\pi r^2} \eta = N_{\text{prev}} , \qquad (3)$$

where

N_{prev} : count of the previous γ-counter,

η : efficiency of the previous γ-counter,

a : sensitive area of the previous γ-counter,

r : distance between the γ-source and the previous γ-counter*,

μ : practical absorption coefficient of lead, which was determined experimentally to be $0.53\ \text{cm}^{-1}$,

x : thickness of the X-ray shield (being 10.5 mm).

We tried to reconstruct carefully the previous γ-counter as well as possible.

Thus, the plateau slope was about 6% per 100 volts and the applied voltage was 1150 V.

Using the result for N_γ as given in §3 and assuming a to be $2\ \text{cm} \times 2\ \text{cm}$, we have calculated by Eq. (3) the efficiency of the previous γ-counter, η, for Li-p γ-rays, obtaining

$$\eta = 15.3 \pm 0.2\% ,$$

the error indicated arising mainly from the measurement of N_γ.

So far we have adopted the value of 22% for η which was calculated by Sonoda. No agreement is found between these two values of η within experimental errors. Now, if the present value of 15.3% is used for the efficiency, the cross section value of $Cu^{63}(\gamma, n)Cu^{62}$ reaction for Li-p γ-rays obtained by Shimizu (**1**), for example, is reduced from 77.5 mb to 33 mb. This corrected value is not inconsistent with our experimental value obtained by the present work (see §4).

The discrepancy between the calculated and experimental values for the efficiency of the previous γ-counter seems to be at least partly due to the X-ray Pb-shield.

In Eq. (3), the effect of the X-ray shield for the γ-ray counting is represented only by a multiplication factor $e^{-\mu x}$, in which μ is the practical absorption coefficient which was obtained by changing the thickness of lead shield. If, however, the Pb thick walled G-M counter is used as a monitor with X-ray shield, it seems to be reasonable that the similar calculations to that for the Pb thick wall must be also made for the X-ray shield. Further, the spectra of gamma rays filtered through the X-ray shield will become quite different from the spectra of the original γ-rays. Hence it is considered to be unreasonable that the calculated value for original γ-rays has been adopted as the value of η in Eq. (3) in the previous works.

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* $r = 29.5$ cm for the previous arrangement (see ref. (**1**)) and $r = 30.2$ cm for the present case.

On the other hand, the experimental efficiency of 15% corresponds to the theoretical one for 13.5 Mev γ-quanta by Sonoda's calculation (3). This estimation is qualitatively reasonable from the viewpoint of degraded gamma rays, but the more quantitative discussions for this point seem to be impossible at this stage of experiment.

From the same reason as mentioned above, the experimental check of the calculation of the efficiency itself cannot be done too.

But it was found that the efficiency of the calibrated γ-monitor counter (Fig. 2) was 25.4% by Hough's method, and agrees well with the calculated value of 23% for Li-p γ-rays within experimental error. It must be noted here, however, that we assumed all secondary electrons from the area of 20 mm in diameter of the lead converter to have entered into the sensitive volume of the G-M tube (Fig. 2).

The comparison between the experimental and theoretical efficiencies of a thick walled γ-ray counter is useful not only for the correction of the cross sections of the photo-nuclear reaction so far studied in our laboratory, but also for obtaining some informations about the interaction of photons and electrons with matter in bulk. More accurate measurements are now in progress with improved arrangements.

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APPENDIX

Angular Distribution of Secondary Electrons by Li-p γ-rays

The angular distribution of the pair electrons is given by Heitler (8) as follows:

$$d\Phi = -\frac{Z^2}{137}\frac{e^4}{2\pi}\frac{P_+P_-dE_+}{k^3}\frac{\sin\theta_+\sin\theta_-d\theta_+d\theta_-d\phi_+}{q^4}$$
$$\times\left\{\frac{p_+^2\sin^2\theta_+}{(E_+-p_+\cos\theta_+)^2}(4E_-^2-q^2)+\frac{p_-^2\sin^2\theta_-}{(E_--p_-\cos\theta_-)^2}(4E_+^2-q^2)\right.$$
$$+\frac{2p_+p_-\sin\theta_+\sin\theta_-\cos\phi_+}{(E_--p_-\cos\theta_-)(E_+-p_+\cos\theta_+)}(4E_+E_-+q^2-2k^2)$$
$$\left.-2k^2\frac{p_+^2\sin^2\theta_++p_-^2\sin^2\theta_-}{(E_--p_-\cos\theta_-)(E_+-p_+\cos\theta_+)}\right\}, \tag{4}$$

with

$$q^2=(\boldsymbol{k}-\boldsymbol{p}_+-\boldsymbol{p}_-)^2.$$

Integrating this with respect to θ_+ and ϕ_+, and using following approximations:

$$(\mu/E_-)^2\ll 1,\qquad (\mu/E_+)^2\ll 1,$$
$$p_-=E_-,\qquad p_+=E_+,$$
$$\theta_-^2\ll 1,\qquad k-E_+=E_-,$$

we obtain a simple formula as

$$\left.\begin{aligned} d\Phi &= A\frac{\theta_-}{\{(\mu/E_-)^2+\theta_-\}^2}, \\ \text{with} \qquad A &= \frac{Z^2e^4}{137k^3}\frac{E_+}{E_-}dE_-d\theta_-, \end{aligned}\right\} \tag{5}$$

where

Z: atomic number, $\mu=m_0c^2$, k: γ-ray energy,
E_+: positron energy, E_-: electron energy,
p_+: positron momentum$\times c$, p_-: electron momentum$\times c$.

By the use of the above equation the angular distributions for $E_-/\mu=10, 17, 25$ are plotted in Fig. 7.

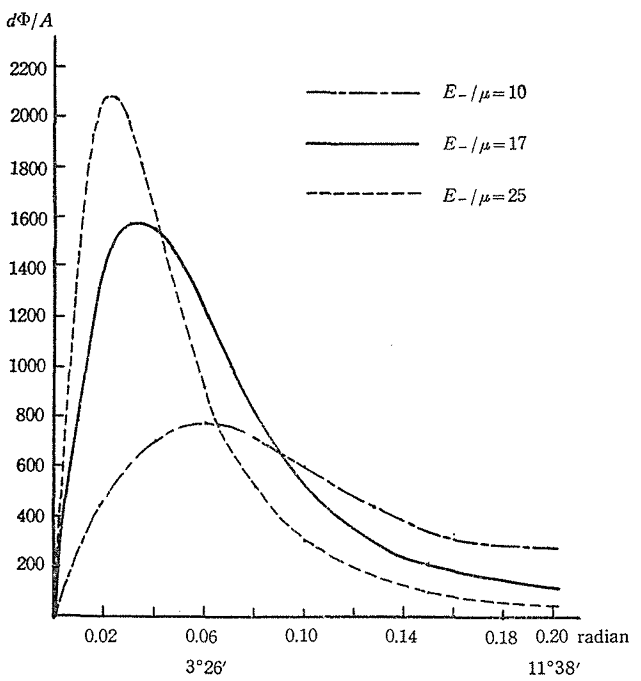

Fig. 7. Angular distribution per unit scattering angle of pair electron.

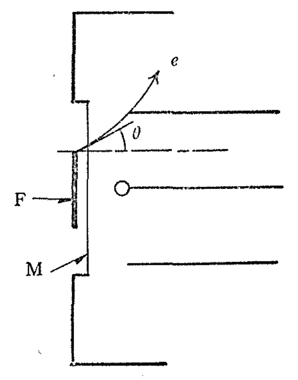

Fig. 8. Counter for converting electron.
F : converter foil
M : mica window
e : path of 8 Mev electron
θ : maximum angle of 8 Mev electron (or positron) entering into the counter

Integrating Eq. (5) with respect to E_- and θ_- over the ranges $2\mu\sim33\mu$ and $0\sim0.2$ radian (equals to 11°38′) for E_- and θ_- respectively, we obtain an approximate value of 17×10^{-24} cm^2 and hence it is found that 95 per cent of the electrons produced by the pair creation are included in this angular range. When electrons of the energy of 8 Mev or more are emitted at most within 30° in the forward direction in the magnetic field, they are expected to enter into the sensitive volume of end-window counter and can be counted (see Fig. 8).

Since, furthermore, either of pair electrons must have the energy of about 8 Mev or more, almost all electrons produced by the pair creation can be counted by the converter counter.

On the other hand, about 13 per cent of the secondary electrons are produced by the Compton scattering and also in this case it is shown by the theory that the majority of them are emitted within about 14° with the energy of 8 Mev or more (see Fig. 9).

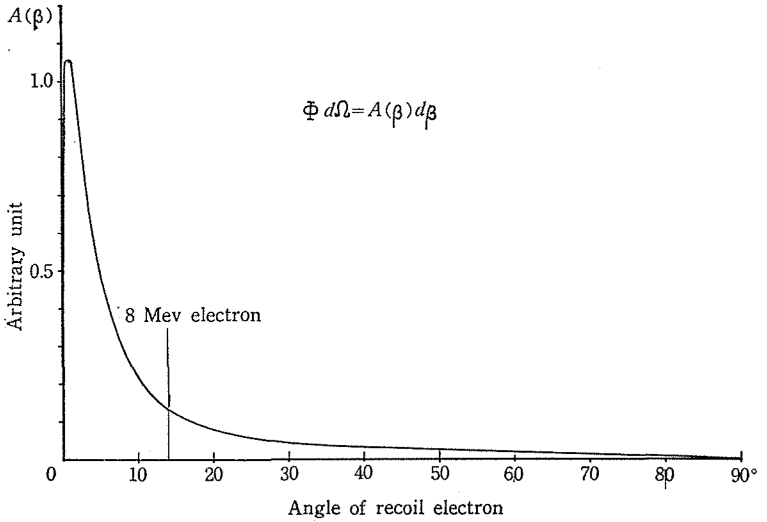

Fig. 9. Recoil electron angular distribution per unit scattering angle of compton scattering by 17.5 Mev γ-rays.

Finally, since for the 14.8 Mev line of Li-p γ-rays the similar considerations seem to be valid, it may be considered that almost all secondary electrons produced by Li-p γ-rays are counted with converter counter.

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