

Detection of Photoelectrons from Heavy Metals

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A detection of photoelectrons produced in tungsten, platinum and lead is investigated by utilization of an end window type Geiger counter. The counting efficiency of gamma rays due to photoelectrons is calculated and measured. For 279.1 KeV gamma rays emitted from ^{203}Hg atoms, the optimum counting efficiency is obtained when a lead foil with 35 mg/cm^2 thick is placed in front of the window of the counter.

1. Introduction

For efficient measurement of low energy gamma rays with a G-M counter, a heavy metal foil having a large atomic number is used in this experiment. The counting efficiency for gamma rays due to photoelectrons is calculated from the photoelectric cross section, angular distribution and transmission probability of photoelectrons and compared with experimental results.

2. Experimental Arrangement

The experimental arrangement is shown in Fig. 1. A gamma ray source of ^{203}Hg shown in Fig. 2 is located at a distance of 7.9 cm from the window of the Geiger counter. The activity of ^{203}Hg radiation source is $3.250 \times 10^6\text{ Bq} \pm 0.1\%$ on Nov. 25, 1977. The decay scheme of ^{203}Hg atoms is given in Fig. 3⁽¹⁾. The counter has a

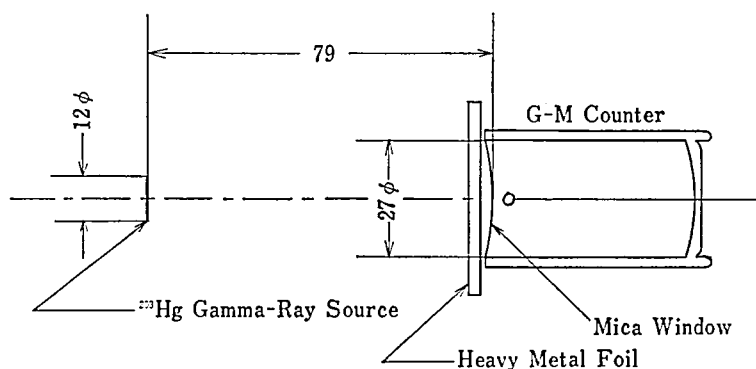


Fig. 1. Experimental arrangement for detecting photoelectrons from heavy metal foils. All dimensions are shown in millimeter.

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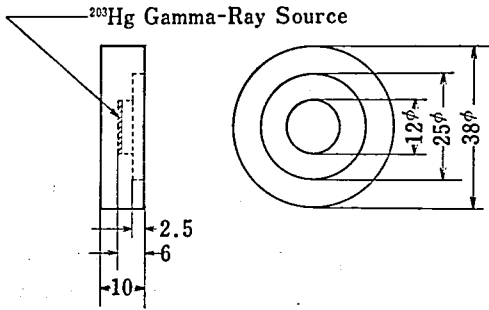


Fig. 2. Gamma ray source ^{203}Hg . All dimensions are shown in millimeter.

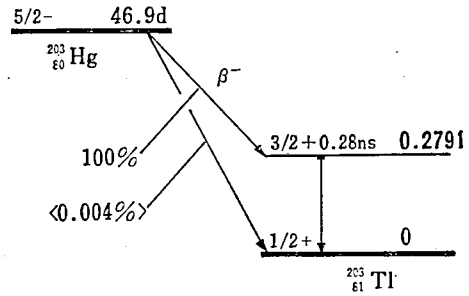


Fig. 3. Decay scheme of ^{203}Hg .

diameter of 2.7 cm and a mica window 1.5 mg/cm^2 thick.

For the detection of photoelectrons from heavy metals, a metal foil of W, Pt or Pb is placed in front of the counter. The source emits 279.1 KeV homogeneous gamma radiation as shown in Fig. 3, some of the gamma photons collide with atoms in the air, metal or mica, and photoelectrons and Compton electrons are ejected. A part of these electrons reach the effective volume of the G-M counter and are counted.

3. Results and Discussions

The counting rate is measured before and after insert a metal foil, with a standard deviation less than 1%.

The intrinsic counting efficiency is obtained from the counting rate and the number of gamma photons struck the counter in unit time, and is given in Table I and Fig. 4. An increase in counting efficiency is observed when a heavy metal foil is placed in front of the window.

When the total thickness of the absorber (plastic container of radiation source, air and mica window) between the radiation source and counter gas is larger than the maximum range of the Compton electron such as this experiment, the production and absorption of Compton electrons are nearly equal, and the Compton electrons emitted from the heavy metal have no contribution to the counting efficiency (see Table I. Al foil).

If a heavy metal foil is placed in front of the window, since the photoelectric cross section is nearly proportional to the 5th power of the atomic number Z , many photoelectrons are produced in the foil and some of them reach the counter and an increase in counting efficiency is given.

As shown in Fig. 4, when the thickness of the metal foil t is very small compared with the range of the photoelectron R_p , the increase in counting efficiency is approximately proportional to the thickness of the foil t . However, if the thickness t is larger than R_p , by the absorption of gamma photons in the metal foil, the counting efficiency decrease exponentially with t .

The optimum thickness t_0 is obtained when the thickness of the foil is a little smaller than R_p . For 279.1 KeV gamma rays, the optimum thickness of the lead foil is found as 35 mg/cm^2 in this experiment. The range of 191.1 KeV photoelectron

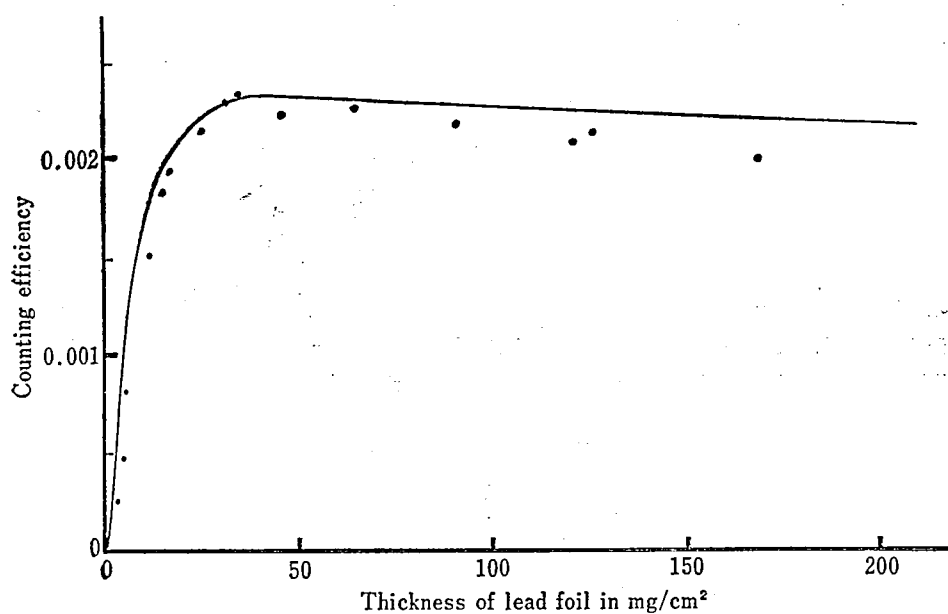


Fig. 4. Variation of counting efficiency due to photoelectrons with thickness of lead foils. Solid curve represents calculated values.

Table I. Counting efficiency for 279.1 KeV gamma rays.

Element of foil	Thickness of foil t (mg/cm ²)	Intrinsic counting efficiency	Increase of counting efficiency by metal foil	Counting efficiency due to photoelectrons
No foil	0	0.00333	0	0
Aluminum	18.99	0.00298	-0.00035	0
Tungsten	204.94	0.00510	0.00177	0.00191
Platinum	205.85	0.00547	0.00214	0.00234
Lead	2.53	0.00358	0.00025	0.00025
	4.64	0.00382	0.00049	0.00049
	4.96	0.00415	0.00082	0.00082
	9.71	0.00472	0.00139	0.00140
	11.10	0.00484	0.00151	0.00152
	14.48	0.00516	0.00183	0.00185
	16.13	0.00527	0.00194	0.00196
	24.49	0.00542	0.00209	0.00213
	30.59	0.00559	0.00226	0.00231
	33.64	0.00563	0.00230	0.00235
	45.06	0.00549	0.00216	0.00223
	64.26	0.00551	0.00218	0.00228
	90.48	0.00539	0.00206	0.00220
	120.51	0.00525	0.00192	0.00210
	126.07	0.00530	0.00197	0.00216
	168.31	0.00510	0.00177	0.00202

Note: In the last column the decrease of secondary electrons from counter gas and counter wall is corrected.

(produced in Pb by 279.1 KeV gamma rays, see Table II.) calculated from the following equation⁽²⁾

$$R=412E_0^{1.265-0.0954 \ln E_0} \quad (1)$$

is 39 mg/cm² in Al. The corrected range by Eq. (5) is approximately 60 mg/cm² in Pb.

Calculation

The binding energy of electrons E_b , kinetic energy of photoelectrons produced by 279.1 KeV gamma rays E and the ratio of the electron velocity to light β are shown in Table II. The cross section for 279.1 KeV gamma rays⁽³⁾ is shown in Table III. The angular distribution of photoelectrons⁽³⁾ is given by

$$P(\theta) = \text{const} \times \beta^2 \sin^2 \theta \left\{ \frac{(1-\beta^2)^{1/2}}{(1-\beta \cos \theta)^4} - \frac{[1-(1-\beta^2)^{1/2}]}{2(1-\beta^2)^{1/2}(1-\beta \cos \theta)^3} + \frac{2[1-(1-\beta^2)^{1/2}]}{4(1-\beta^2)(1-\beta \cos \theta)^3} \right\}, \quad (2)$$

and is shown in Fig. 5, where θ is the angle between the incident direction of the photon and the ejected direction of the photoelectron.

Detection probability of photoelectrons

A photoelectron produced at the point A in Fig. 6. x g/cm² from the surface of the foil, and emitted in the direction θ will reach the counter with the probability $T(x, \theta)$ after multiple scattering. The directional distribution of the scattered electrons is essentially a Gaussian distribution⁽⁴⁾, and the probability $T(x, \theta)$ depends upon x and θ on an average.

Table II. Binding energy of electron E_b , kinetic energy of photoelectron E and ratio of electron velocity β for 279.1 KeV gamma rays. (E of L electron is average value of L_I , L_{II} and L_{III})

Element	Electron in atom	E_b (Kev)	E (KeV)	β
Tungsten	K shell	69.5	209.6	0.7051
	L shell	11.3	267.8	0.7546
Platinum	K shell	78.4	200.7	0.6960
	L shell	12.9	266.2	0.7535
Lead	K shell	88.0	191.1	0.6858
	L shell	14.7	264.4	0.7521

Table III. Cross section for 279.1 KeV gamma rays⁽³⁾. (in units of barn)

Element	Compton effect	Photoelectric effect
Tungsten	26.85	87.82
Platinum	28.30	108.67
Lead	29.75	127.56

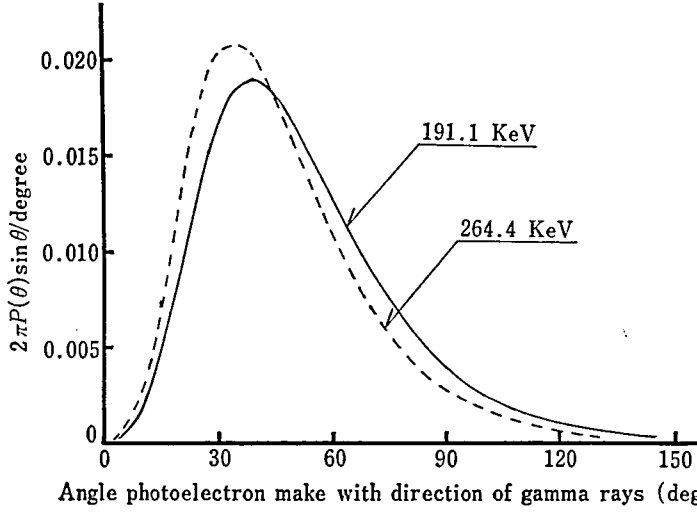


Fig. 5. Angular distribution of 191.1 KeV and 264.4 KeV photoelectrons⁽³⁾.

In this calculation, an assumption was made that the photoelectron produced at A in Fig.6 and ejected in the direction θ has the transmission probability⁽⁵⁾ of

$$T(x, \theta) = T(x_\theta) = \frac{1 + \exp(-S_0)}{1 + \exp\left[\left(S_0 + 2\right) \frac{x_\theta}{R_{ex}} - S_0\right]}, \quad (3)$$

where

$$x_\theta = x \sec \theta + (x_m)_c \sec \theta. \quad (4)$$

In Eq. (3), R_{ex} is the extrapolated range⁽⁵⁾ and S_0 is the empirical parameter⁽⁵⁾, and the calculated values are shown in Table IV. In Eq. (4), $(x_m)_c$ is the converted value of mica to heavy metal thickness. Because of the range of electron is represented by

$$R = \int \left(-\frac{dE}{dx} \right)^{-1} dE, \quad (5)$$

$(x_m)_c$ may be written by

$$(x_m)_c = x_m \frac{\left\langle -\frac{dE}{dx} \right\rangle_{\text{mica}}}{\left\langle -\frac{dE}{dx} \right\rangle_{\text{metal}}}, \quad (6)$$

x_m in Eq. (6) is the thickness of mica in unit of g/cm².

In this calculation, from equations described above, the detecting probability of photoelectrons produced x g/cm² from the surface of the foil can be written

$$D(x) = \int T(x_\theta) P(\theta) d\Omega = 2\pi \int_0^{\frac{\pi}{2}} T(x_\theta) P(\theta) \sin \theta d\theta. \quad (7)$$

Counting efficiency due to photoelectrons

For the calculation of counting efficiency, the attenuation of gamma rays must be considered. At the point A in Fig. 6, the intensity of gamma radiation is

$$I = I_0 e^{-\sigma N(t-x)}, \quad (8)$$

where I_0 is the initial intensity at $x=t$, σ is the total cross section and N is the number of atoms per unit mass in the metal foil.

The counting efficiency due to photoelectrons ejected from K shell and L shell may be written from Eq. (7) as

$$\eta_K = (\sigma_f)_K N \int_0^t D_K(x) e^{-\sigma N(t-x)} dx \quad (9)$$

and

$$\eta_L = (\sigma_f)_L N \int_0^t D_L(x) e^{-\sigma N(t-x)} dx, \quad (10)$$

respectively, where σ_f is the photoelectric cross section and $(\sigma_f)_K$ and $(\sigma_f)_L$ are the cross sections due to the electrons in the K shell and L shell, respectively. In this calculation $(\sigma_f)_K$ is $0.8 \sigma_f$ and $(\sigma_f)_L$ is $0.2 \sigma_f$.

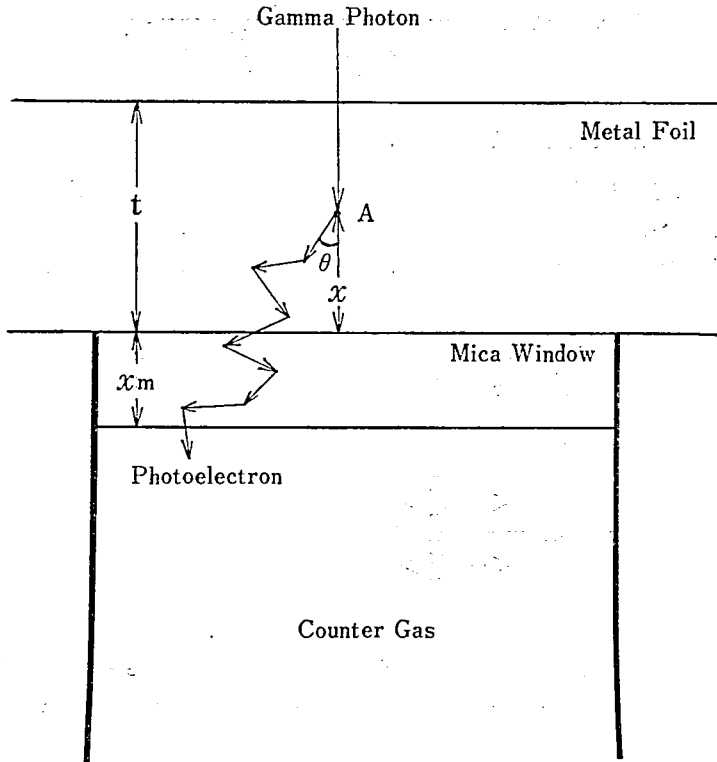


Fig. 6. Relation between G-M counter and photoelectron.

The increase in counting efficiency due to photoelectrons is obtained as

$$\eta = \eta_K + \eta_L.$$

The computed values of counting efficiency are given in Table V. and Fig. 4. These values are nearly agree with experimental results.

Table IV. Extrapolated range R_{ex} and parameter S_0 in Eq. (3)⁽⁵⁾.

Element	Electron in atom	$R_{ex}(\text{mg}/\text{cm}^2)$	S_0
Tungsten	<i>K</i> shell	24.50	0.7898
	<i>L</i> shell	35.41	0.7956
Platinum	<i>K</i> shell	21.72	0.7493
	<i>L</i> shell	33.23	0.7555
Lead	<i>K</i> shell	19.09	0.7119
	<i>L</i> shell	31.12	0.7185

Table V. Computed counting efficiency of G-M counter due to photoelectrons for 279.1 KeV gamma rays emitted from ^{203}Hg in units of count per photon.

Element	Thickness of foil t (mg/cm ²)	η_K	η_L	η
Tungsten	5	0.00073	0.00021	0.00094
	10	0.00117	0.00037	0.00154
	15	0.00142	0.00048	0.00190
	20	0.00151	0.00056	0.00207
	40	0.00174	0.00071	0.00245
	60	0.00175	0.00072	0.00247
	80	0.00174	0.00072	0.00246
	100	0.00172	0.00072	0.00244
	150	0.00169	0.00071	0.00240
	200	0.00166	0.00069	0.00235
	205	0.00165	0.00069	0.00234
Platinum	5	0.00079	0.00024	0.00103
	10	0.00123	0.00042	0.00165
	15	0.00146	0.00054	0.00200
	20	0.00157	0.00063	0.00220
	40	0.00172	0.00077	0.00249
	60	0.00172	0.00066	0.00238
	100	0.00168	0.00078	0.00246
	150	0.00164	0.00077	0.00241
	200	0.00161	0.00075	0.00236
	205	0.00161	0.00075	0.00236
Lead	5	0.00082	0.00026	0.00108
	10	0.00124	0.00044	0.00168
	15	0.00143	0.00057	0.00200
	20	0.00152	0.00065	0.00217
	40	0.00157	0.00076	0.00233
	60	0.00156	0.00077	0.00233
	80	0.00154	0.00077	0.00231
	100	0.00153	0.00076	0.00229
	150	0.00150	0.00074	0.00224
	200	0.00146	0.00073	0.00219

4. Conclusions

With an ordinary G-M counter or proportional counter, it is generally difficult to make an accurate measurement in a short time, because of the low counting efficiency for gamma rays. However, we were able to improve the counting efficiency by inserting a foil of metal with large atomic number. The effect may be much more significant, when the energy of gamma photons or X-rays is very low.

References

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