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The Photo-disintegration of Beryllium by the High Energy Gamma-Rays

By

Bunsaku Arakatsu, Masateru Sonoda, Yoshiaki Uemura, Shinjiro Yasumi, and **Yoshio Saji**

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1. Introduction

After the discovery of Chadwick and Goldhaber, the phenomenon of the photo-disintegration of Beryllium was studied both experimentally and theoretically by several workers (1) for the γ-rays of comparatively low energies up to about 3 Mev. There are, however, no literatures known to us concerning the investigation for the γ-rays of higher energies.

In our laboratory, it was previously studied (2) that the α-particles may be suspiciously ejected from various nuclei when they are irradiated by the high energy γ-rays of (Li–p) and (F–p) reactions. However, owing to the lack of the observed number of pulses and cloud chamber tracks, no decisive conclusion was given there. We have recently repeated the experiments under the improved conditions and obtained some conclusive results. In the present paper, the results of observation with Beryllium will be given.

2. Apparatus

The γ-rays of 17.6 Mev and 6.13 Mev were produced by bombarding thick target of Lithium metal and Calcium fluoride with protons of energy of 500 Kev and 350 Kev respectively. The hydrogen ion beam amounting to 30～50 microamperes was, in this case, directed upon the target unseparatedly.

Two proportional counters of methane gas flow type (3), which are made of brass cylinder 3.6 cm in diameter and 20 cm in effective length, are placed parallel at the distance of 6.5 cm from the target as shown in Fig. 1. The inner surface of one of the counters is coated with thick layer of Beryllium oxide and the other is uncoated. The γ-ray counter of lead wall 6.5 mm in thickness (4) is placed at 29.5 cm from the target, being shielded by a lead cylinder of 1.05 cm in thickness.

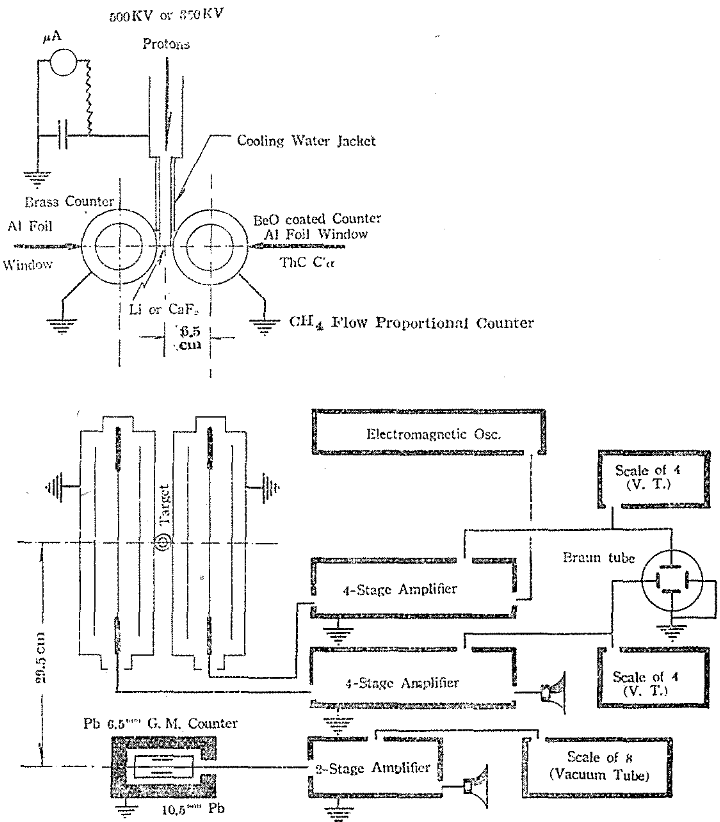


Fig. 1.

The pulses due to the α–particles ejected from the walls of the counters were counted usually by two scale-of-4 scalers, after having been amplified by the respective 4–stage linear amplifier. In order, however, to discriminate a spurious count due to an accidental electromagnetic induction from the accelerating tube, special cares were taken to the device. The pulses from each of the counters were fed respectively into the vertical and horizontal deflectors of a Braun-tube oscilloscope (Fig. 1), so as the spurious pulse which took place simultaneously in both counters appeared as an oblique pulse on the oscilloscope screen and the number of these kicks were subtracted from the counts. It was found that in general the spurious pulses were seldom in winter, when the conditions of the high tension apparatus and the accelerating tube system were good.

The linearity of the counter and amplifier system was ascertained by observing the integrated Bragg curve in the methane gas (5), for the various distances of a sample of Thorium deposit from the counter window.

3. Experiments

(i) When the counters were irradiated by the γ-rays, many pulses due to α-particles were observed in the Be-coated counter, but very few in the uncoated one. Moreover, the number of observed pulses from the Be-coated counter was found to be exactly proportional to that of the γ-ray counter. A part of the experimental data is shown in Table I for the case of (Li-p) γ-rays.

TABLE I.

	Number of pulses by Be-coated counter		Number of pulses by uncoated counter
Proton energy	500 Kev	375 Kev	500 Kev
γ-counts	119804	1643	28449
α-counts	2800	36	39
$\frac{\alpha\text{-counts}}{\gamma\text{-counts}}$	2.34×10^{-2}	2.19×10^{-2}	1.37×10^{-3}

These facts show that the observed pulses from the Be-coated counter are definitely to be attributed to the α-particles ejected from Beryllium irradiated by the γ-rays, but not to the particles emitted by (n-α) reaction induced by the neutrons which might be produced by the (D-D) and (Li-D) reactions at the target. During the course of our experiments, it was found that the height of the pulses in this case were found most frequently to be nearly equal on the screen of the Braun-tube oscilloscope. This aspect may be attributed to the fact that the range of the emitted α-particles are in most cases sufficiently long to pass across the tube diameter and reach the opposite surface of the counter wall.

(ii) Another counter of larger diameter was therefore constructed and the similar experiments were repeated. The inner diameter of the new counter is 6 cm, while the effective length of which is 20 cm as before. Beryllium oxide is coated in the inner surface to the thickness of 7.49 mg/cm^2. The linearity of the counter and amplifier system was ascertained as previously. After having been amplified, the output pulses were counted by the scalers and at the same time observed on the oscilloscope screen as in the previous experiments. Furthermore, an electromagnetic oscillograph (6) was used to record the pulses on the printing paper. The pulse-height distribution was in this way carefully determined for each case. Fig. 4 is a part of the oscillograph records for the case of (Li–p) γ–rays. The pulse-height was daily calibrated by comparing with that of the α–particles from a Thorium deposit. An example of the calibration curve is shown in Fig. 2, in

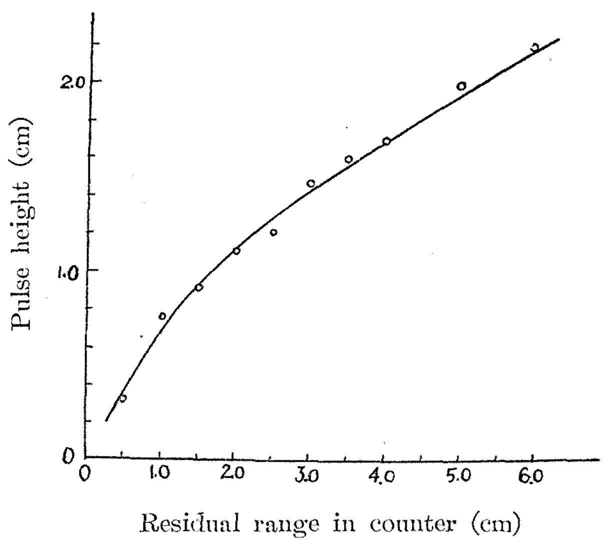


Fig. 2.

which the abscissa is the residual range in the counter and the ordinate is the pulse-height on the oscillograph record. The solid curve is the integrated Bragg curve calculated from Tayler's data (5), and the conformity with experiments (a series of dotted marks) is taken to be sufficiently good.

By using this calibration curve, the range distribution was obtained for the α–particles emitted by the photo-disintegration process. The results are shown in Fig. 3 for the cases of (Li–p) and (F–p) γ–rays, in which the number of pulses having the range greater than r is plotted against r.

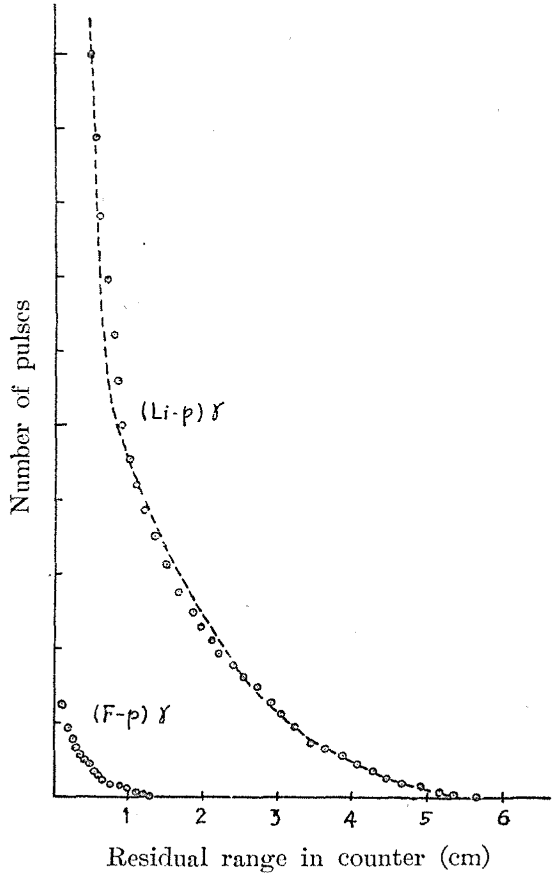


Fig. 3.

4. Explanation of the phenomena, together with discussions

Let us now try to give the explanation of the disintegration processes occurred in Beryllium nucleus irradiated by these γ–rays and estimate their cross-sections by analysing the range distribution curves shown in Fig. 3.

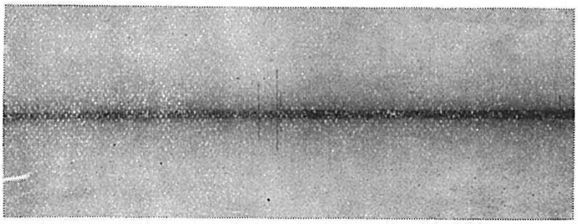
(i) From the figure, we see that the maximum range is about 5.8 cm in the case of (Li–p) γ–rays. And so, from the consideration of mass and energy, the following processes are taken to be possible, namely :

$$\left.\begin{aligned} Be^9 + (\text{Li–p})\gamma &\rightarrow Be^{8*} + n\,, \\ Be^{8*} &\rightarrow 2\alpha\,, \end{aligned}\right\} \qquad (1)$$

where the residual nucleus Be^{8*} is considered to be remained either in the ground state or in an excited state of energy 3.0, 4.8, or 7.0 Mev (7). If we assume the process (1) to be the case, the maximum range of the emitted α-particle is expected by simple calculations to be as shown in the second and third columns of Table II for each of the above-mentioned states of recoiling Be^{8*} nucleus.

TABLE II. Maximum range of α-particles calculated for different energy states of Be^{8*} excited by γ-rays of various energies.

Energy of excited state of Be^{8*} (Mev)	Maximum range of α-particle in cm		
	(Li-p) γ-rays		(F-p) γ-rays
	$h\nu$=17.6 Mev	$h\nu$=14.8 Mev	$h\nu$=6.13 Mev
0	0.70	0.64	0.33
3.0	2.84	2.47	1.25
4.8	4.05	3.52	——
7.0	5.49	4.71	——



Oscillo. No. 130

Oscillo. No. 132

Fig. 4. Oscillograph records for Be^9+17.6 Mev γ (29/VI 1950).

Both of the alternative considerations, namely the splitting reaction:

$$Be^9 + (\text{Li-p})\gamma \rightarrow 2\alpha + n\,, \qquad (2)$$

and the simple fission process:

$$Be^9 + (\text{Li–p})\gamma \rightarrow He^4 + He^5, \tag{3}$$

followed by

$$He^5 \rightarrow \alpha + n \tag{3'}$$

are considered to be energetically impossible, since the observed maximum range is 5.8 cm in air.

Indeed, however, when the energy of the γ–rays is 14.8 Mev, the reaction (3) seems to be possible (maximum range = 5.99 cm). But, if it were the case, it had to appear a steep step in the observed curve in Fig. 3 at the range of 4.59 cm due to the homogeneous group of α–particles.

Now, by the reaction (1), Be^{8*} is considered to split up into two α–particles with the mean life of about $10^{-15} \sim 10^{-17}$ seconds (8). If the spherical symmetry in the center of gravity system is assumed in the splitting up of Be^{8*}, the number $n(\theta)$ of the α–particles emitted from unit volume of sample at an angle θ with the direction of recoil of Be^{8*}, will be given by

$$n(\theta)\,d\theta = \frac{\sigma N n_\gamma}{4\pi} 2\pi \sin\theta\, d\theta\,, \tag{4}$$

where σ is the cross-section of photo-disintegration, N the number of Be^9 nuclei per unit volume, n_γ the number of γ–ray quanta falling on the unit area of Be layer, and θ is measured in the center of gravity system. The range of the emitted α–particle is determined as a function of θ and it is denoted by $R(\theta)$.

When the homogeneous α–particles of the range $R(\theta)$ are emitted from a thick target, the probability that the residual range in the counter volume is greater than r is given by a simple calculation as

$$\frac{R-r}{4s}\,,$$

where s is the stopping power of BeO relative to air. Then the total number of the α–particles having the residual range greater than r will be

$$N_\alpha = \frac{\Omega'}{4\pi}\,\frac{\sigma N N_\gamma}{8s}\int_0^{\theta_0} (R-r)\sin\theta\, d\theta\,, \tag{5}$$

where N_γ is the total number of γ–ray quanta emitted from the source, θ_0 the value of θ corresponding to r in the R–θ relation, and Ω' the solid angle, modified by taking the oblique incidence of γ-quanta into account.

We can now analyse the observed range distribution curve by using equation (5). Unfortunately, however, since the effects by the two components of (Li–p) γ-rays, namely 17.6 and 14.8 Mev lines (**9**), could not be separated by the observed curve in our experiments, we have to consider the whole effect presumably as solely due to the 17.6 Mev line.* Then we can explain the portion of the longer and shorter range of the observed distribution curve as due to

$$\left.\begin{array}{l} Be^9 + 17.6\,\text{Mev}\ \gamma \rightarrow Be^{8*} + n\,, \quad \text{(7 Mev excited)} \\ Be^{8*} \rightarrow 2\alpha\,, \end{array}\right\} \qquad (6)$$

and

$$\left.\begin{array}{l} Be^9 + 17.6\,\text{Mev}\ \gamma \rightarrow Be^{8} + n\,, \quad \text{(ground state)} \\ Be^{8} \rightarrow 2\alpha\,, \end{array}\right\} \qquad (7)$$

respectively.

The range distribution curve calculated under the assumption of the processes (6) and (7) is shown by the dotted line in the figure. The conformity with the observed curve is fairly satisfactory for the range longer than about 2.5 cm. It seems, however, that there remains a small deviation for the range smaller than the value, which cannot be explained by any process shown in Table II. It may probably be attributed to the fact that the pulses of smaller height are observed more frequently than they are theoretically expected, because of the effect of the cylindrical shape of the counter. A more precise experiment will be necessary to derive conclusion as to this point.

To obtain the cross-section for each process, it is necessary to know the counting efficiency of the γ-ray counter. This quantity was previously calculated by one of the authors (**10**) and found to be

23.8 % for 17.6 Mev γ-rays,

18.1 % for 14.8 Mev γ-rays,

and 3.2 % for 6.13 Mev γ-rays,

respectively, for the lead-walled counter used in our experiments.

* According to Walker and McDaniel (**9**), the ratio of intensities of the lower energy line to the higher energy line is found to be 0.50 at 0.46 Mev protons.

The practical absorption coefficient of the lead cylindrical shield covering the γ–ray counter was carefully measured for both of the γ–rays and was found to be

$$\mu_{\text{Li-p}} = 0.53\ \text{cm}^{-1},$$

and

$$\mu_{\text{F-p}} = 0.40\ \text{cm}^{-1},$$

respectively.

The actual readings of the γ–counts were corrected thereby in computing the absolute number of γ–quanta emitted from the target. Using these values, the cross-section with which the Be^{8*} nucleus is produced by the γ–rays could be estimated and it is given as

$$\sigma_{17.6} = 2.15 \times 10^{-27}\,\text{cm}^2 \quad \text{for the 7 Mev excited state,} \tag{8}$$

and

$$\sigma_{17.6} = 5.1 \times 10^{-26}\,\text{cm}^2 \quad \text{for the ground state,} \tag{9}$$

respectively.

(ii) For the (F–p) γ–rays, the observed number of α–particles is very small compared to the case of (Li–p) γ–rays. The maximum range was found to be about 1.5 cm and the process shown in the last column of Table II seems therefore to be possible. We may interpret the observed curve as the superposition of the following two processes:

$$\left.\begin{array}{ll} Be^9 + 6.13\ \text{Mev}\ \gamma \rightarrow Be^8 + n\,, & \text{(ground state)} \\ Be^8 \rightarrow 2\alpha\,, & \end{array}\right\} \tag{10}$$

and

$$\left.\begin{array}{ll} Be^9 + 6.13\ \text{Mev}\ \gamma \rightarrow Be^{8*} + n\,, & \text{(3 Mev excited)} \\ Be^{8*} \rightarrow 2\alpha\,. & \end{array}\right\} \tag{11}$$

Now, as shown in Table II, the maximum range of α–particle is about 0.33 cm and 1.25 cm respectively for the cases expressed in (10) and (11). We may explain in this way the part of range longer than 0.33 cm presumably by the process (11).* However, the shape of the range distribution curve calculated for this process is found to change more rapidly with the range than that of the observed one.

* Recently, Miller and Cameron (**11**) have reported that the 3 Mev excited state of Be^{8*} appears in the photo-disintegration of C^{12} by the X–rays from a 24 Mev betatron. This is not consistent with our results, though no decisive conclusion could be derived owing to the lack of their number of observed pulses.

On the other hand, we see that the part of range smaller than 0.33 cm is nearly consistent with process (10). There will therefore remain a small unexplained part of the range from 0.33 to 1.5 cm similarly to the case of (Li–p) γ–rays.

Now, for the sake of simplicity, if the process (10) is solely considered in the case of (F–p) γ–rays, we obtain

$$\sigma_{6.13} = 1.62 \times 10^{-27}\,\mathrm{cm}^2 \tag{12}$$

as the roughly estimated value of the cross-section for the ground state of Be^8.

From (9) and (12), it can be concluded that the cross-sections of the process

$$Be^9 + h\nu \rightarrow Be^8 + n \quad (Be^8 \text{ in the ground state})$$

are 5.1×10^{-26} and $16.2 \times 10^{-28}\,\mathrm{cm}^2$ for the 17.6 and 6.13 Mev γ–rays respectively.

According to the theoretical calculation by Guth and Mullin (**1**), the cross-section is about $15 \times 10^{-28}\,\mathrm{cm}^2$ for the 6.13 Mev γ–rays and it decreases monotonously with the energy of the γ–rays in the energy range under consideration.* The observed value is, in the case of 6.13 Mev γ–rays, nearly equal to the theoretical one, but it increases with the energy of the γ–rays in our energy range, which is contradictory to the theoretical expectation. This discrepancy may probably be ascribed to the fact that the assumptions made by Guth and Mullin do not hold for the γ–rays of such high energies, in which the Be^9 nucleus is taken to consist of the inert Be^8 core and a "valence" neutron moving around it in the ground $P_{\frac{3}{2}}$ state and the electric dipole transitions take place when it is irradiated by the γ–rays.

It is to be noted that the excited states of Be^{8*} of 4.8 Mev and probably also 3.0 Mev which were observed in the nuclear reactions by high speed ions (**7**) seem to have no contribution in the photo-disintegration process.

From the above consideration, it may be concluded that the Be^9 nucleus emits a neutron when irradiated by the γ–rays and then the residual Be^8 nucleus splits up into two α–particles. We previously observed (**12**) that a fission process took place in the nucleus of Uranium or Thorium irradiated by the high energy γ–rays. Comparing the photo-fission process of Uranium and Thorium to the photo-

* Miller and Cameron (**11**) found one event which may be explained as the photo-disintegration of C^{12} via the ground state of Be^8.

disintegration of Be^9 nucleus, it may be presumably considered that the nucleus of Uranium or Thorium emits at first a neutron when irradiated by the γ-rays and then splits up into two nuclei of intermediate mass.

More precise experiments are now in progress by using a photographic emulsion and a deep ionization chamber with a grid.

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Nuclear Research Laboratory,
Institute of Physics,
University of Kyoto.