INTERACTION OF HARD γ-RAYS WITH ATOMIC NUCLEI*

BY C. Y. CHAO (趙忠堯) AND T. T. KUNG (龔祖同)†

Department of Physics National Tsing Hua University

Received Jan. 3, 1934

Abstract

With γ-rays of various wave-lengths the number of counts produced in a Geiger-Müller counter of Pb-wall was determined in equal time intervals. The same experiment was carried out with a counter of Al-wall. Let N_{Pb} and N_{Al} represent the number of counts produced in the Pb-counter and Al-counter respectively by a beam of γ-rays of even wave-length in a given time interval. The ratio N_{Pb}/N_{Al} observed decreases at first with the wave-length of the incident beam due to the diminishing photo-electric of lead. It is, however, found to increase by 16% when the wave-length of the incident radiation is decreased from a value 6.6 x. u. 4.7 x. u. This rising is due to particles produced by the interaction of hard γ-rays with the Pb-nuclei.

Introduction

The absorption of hard γ-rays of ThC″ in lead is known to consist of two parts, the absorption by shell-electrons and the absorption by atomic nuclei. The nuclear absorption is also accompanied by the emission of characteristic radiations of frequencies different from that of the primary.[1] One of us

*Chao and Kung, Nature, vol. 132, p. 709 (1933).

†Research fellow of the China Foundation.

(1) Chao, Phy. Rev. vol. 36, p. 1519 (1930), Gray and Tarrant, Proc. Roy. Soc. A, vol. 136, p. 662 (1932).

had estimated the intensity of such radiations and found that the total number of quanta of the characteristic radiations emitted was roughly equal to the total number of primary quanta absorbed by the nuclei. The total energy of the radiations emitted was, however, much smaller than the total energy absorbed.[2] Similar conclusions were reached by Gray and Tarrant though with different details.[3] It was thought that a nuclear disintegration[4] might occur in such a process and a part of the absorbed energy is thereby spent. With this point of view, we have tried to detect any particles which might be ejected from the Pb-nuclei by the primary γ-quanta. As result, particles other than Compton recoil electrons or ordinary photo-electrons were observed from lead when irradiated with hard γ-rays, and they were previously regarded by us as indicating a process of the nuclear disintegration. At this point, we are very grateful to Lord Rutherford who pointed out, in a note, that our experimental result is in agreement with the recently advanced view that a γ-quantum of high energy can be converted into a pair of electrons, one positive and one negative, in the strong field of the nucleus. This explanation is to be understood in the following description when we talk about the particles ejected from the nucleus.

The Experiment

In order to detect particles ejected from the Pb-nuclei, two Geiger-Müller counters, one of Al-wall and the other of Pb-wall, were used. Aluminium was chosen as standard to be compared with since the nuclear absorption of ThC″ γ-rays in aluminium is much smaller than that in lead. Let N_{Pb} and N_{Al} be the number of counts produced in unit time in the Pb-counter and Al-counter respectively by a given beam of γ-rays. Each of these numbers will be a measure of the number of electrons

(2) Chao, Science Reports of Tsing Hua Univ. First Series, vol. 1, p. 159 (1932).

(3) loc. cit.

(4) Chao, Proc. Roy. Soc. A, vol. 135, p. 206 (1932).

ejected in the wall of the corresponding counter. The ratio N_{Pb}/N_{Al} as a function of the wave-length of incident γ-radiation will at first decrease with decreasing λ due to the diminishing photo-electric effect of lead. As the wave-length further decreases, the ratio N_{Pb}/N_{Al} might, however, rise, if particles be ejected from the Pb-nuclei by γ-quanta of wave-length less than a certain value and they add themselves to N_{Pb}.

In measuring the ratio N_{Pb}/N_{Al} for γ-rays of various wave-lengths, we adopted a primary beam of γ-rays of ThC″ and also the scattered beams at various angles when a primary beam was incident on an iron scatterer. The wave-length in x. u. of the scattered beams can be calculated from Compton-Debye's formula:

$$\lambda = \lambda_0 + 24.2(1 - \cos\theta),$$

where $\lambda_0 = 4.7$ x. u. is the wave-length of primary beam and θ is the angle of scattering, the nuclear scattering of iron being small compared to Compton scattering in forward directions. The γ-ray source was a Rd-Th preparation of 9 mg Ra-equivalent for the production of scattered beams, and another preparation of 1 mg Ra-equivalent was used for the production of the direct beam. The primary beam was filtered through 2 cm of lead in both cases.

The experimental arrangement is shown in Fig. 1. The γ ray source was screened by lead blocks at least 15 cm on each side. The iron scatterer was 3×3×4 cm in size. The distance between the scatterer and the counter was 24 cm for the scattering angle of 23° and for other angles it was such that the number of counts per unit time was approximately the same as that for 23°. A thin piece of lead was inserted between the scatterer and the counter to prevent any electrons ejected from the scatterer to shoot into the counter. For the measurement with the primary beam, the Rd-Th preparation was set at a distance of 225 cm from the counter.

The Al- and Pb-counters had equal inner dimensions (4 cm long and 2 cm diameter) and approximately equal mass per

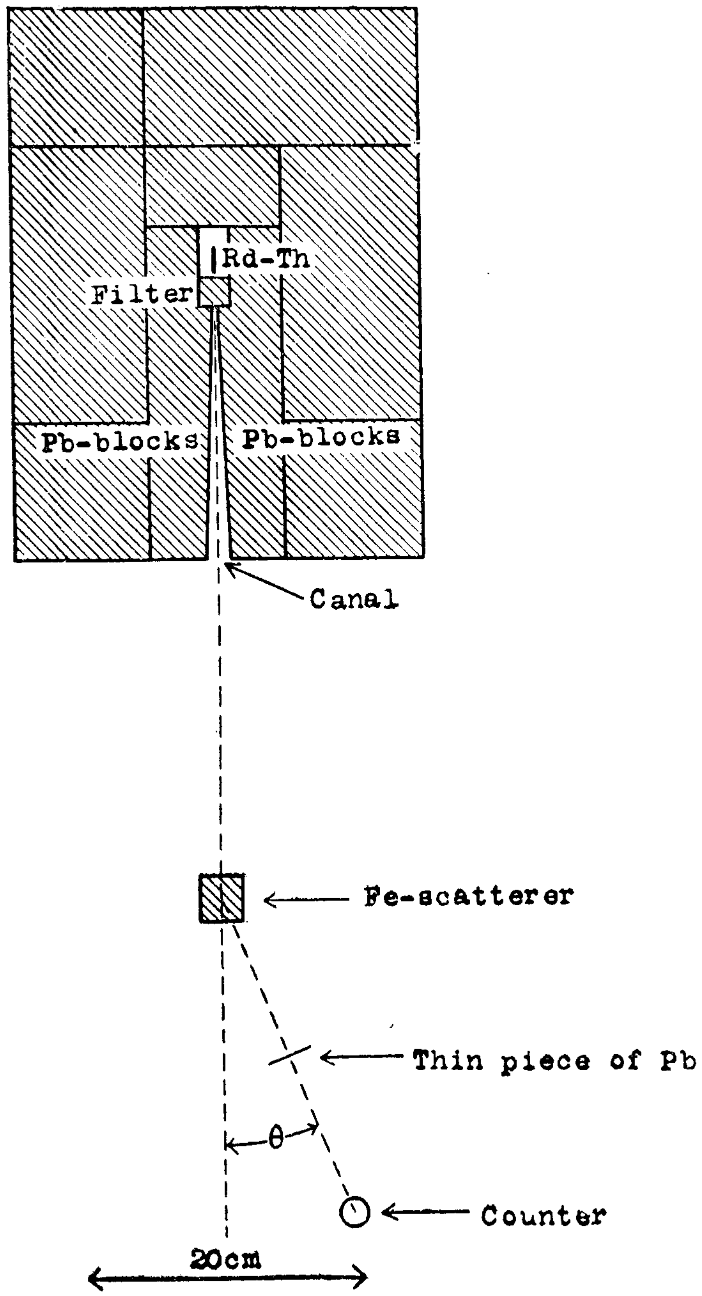
Rd-Th
Filter
Pb-blocks
Pb-blocks
Canal
Fe-scatterer
Thin piece of Pb
θ
Counter
20cm

Fig. 1

square cm of the wall. They had bare copper filament of diameter 0.4 mm, and were filled with dry air at a pressure of 5 cm Hg. Since a Geiger-Müller counter only registers those electrons which are able to emerge from the counter wall, it is desirable to make the counter walls as thin as possible to reduce the percentage of ejected particles retained in the wall itself. This, however, was limited by the deformation of the Pb-counter under pressure. We succeeded to construct a Pb-counter of quite thin wall (0.22 mm) without any deformation when evacuated to a pressure of 5 cm Hg by using an alloy of 4% antimony and 90% lead, the wall-thickness of Al-counter being 0.92 mm.

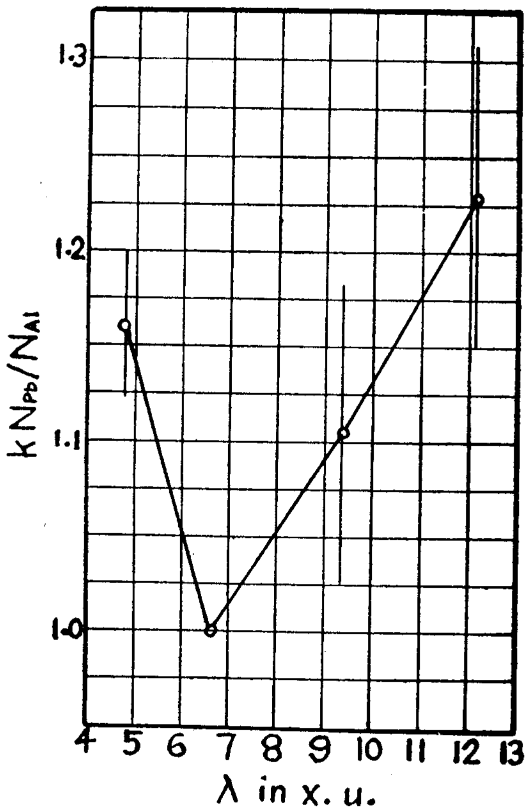

Fig. 2

In taking readings the counter was connected to a resistance capacity coupled amplifier, the number of counts was registered by a magnetic relay. With the counter at a given position the number of counts in equal time intervals was registered with and without the beam of γ-rays successively. The difference of the two readings gave the number of counts produced by the beam of γ-rays. For each wave-length the number of counts in a given time interval was measured alternately with that for $\lambda=6.6$ x. u., hence the ratio N_{Pb}/N_{Al} for each wave-length was determined relatively to that for $\lambda=6.6$ x. u. The frequency of occurence of counts being subjected to statistical fluctuations, only the average of a great number of consistent readings can give a reasonably accurate result. We have taken many sets of reading (over 16,000 counts for each wave-length in each counter) and the following results are the mean of them.

Results

The result is shown in Table I and graphically in Fig. 2, where N_{Pb}/N_{Al} is multiplied by a constant k such that the value $k\,N_{Pb}/N_{Al}$ at 23° is unity. In Fig. 2 the vertical line at each point represents the probable error due to statistical fluctuations.

Table I

	λ (x. u.)	$k\,N_{Pb}/N_{Al}$
Primary radiation	4.7	$1.16\pm.04$
Scattered radiation at 23°	6.6	$1.00\pm.00$
Scattered radiation at 36°	9.35	$1.11\pm.08$
Scattered radiation at 46°	12.1	$1.23\pm.08$

In Fig. 2 the ratio N_{Pb}/N_{Al} is seen to decrease from $\lambda=12.1$ x. u. to $\lambda=6.6$ x. u., but from $\lambda=6.6$ x. u. to 4.7 x. u. it rises as was expected if particles were ejected from Pb-nuclei by the hard radiation of $\lambda=4.7$ x. u. The difference of the two ratios for $\lambda=6.6$ x. u. and 4.7 x. u. is about 16%.

Discussion

(a) It might seem that the rising of the ratio N_{Pb}/N_{Al} for $\lambda=4.7$ x. u. may also result from a difference in the scattering effect of the Pb-nuclei and Al-nuclei towards the Compton recoil electrons produced in the counter walls by the incident γ-rays. For, the Pb-nuclei owing to their greater scattering power, reduce the range (i. e. the thickness that can be penetrated) of the recoil electrons and consequently reduce the number of electrons emerging from the counter wall more markedly than the Al-nuclei in the corresponding case; and this effect is smaller for harder radiations so that the ratio N_{Pb}/N_{Al} might be appreciably greater for γ-rays of $\lambda=4.7$ x. u. than for 6.6 x. u. If this were the case, the difference of the ratios for $\lambda=6.6$ x. u. and 4.7 x. u. should be more pronounced by using counters of thicker walls since the effect of scattering increases with thickness of the wall. But the same result (i. e. a difference of about 16% between the two ratios) was found when the experiment was repeated with a Pb-counter of 0.3 mm wall-thickness and an Al one of 1.2 mm.

We have also other evidences which support the view that the difference of the two ratios N_{Pb}/N_{Al} for $\lambda=4.7$ and $\lambda=6.6$ x. u. is due to particles ejected from the Pb-nuclei. These are given below.

(b) Let $(n_e)_{Pb}$ and $(n_e)_{Al}$ be the number of shell-electrons per square cm of the wall of the Pb-counter and Al-counter respectively, σ_e be the Compton scattering coefficient per electron, and τ_e the photo-absorption coefficient per electron of lead.[5] Then the ratio of the number of shell-electrons ejected in the Pb-wall to that in Al-wall by the same γ-ray beam is

$$\frac{(n_e)_{Pb}}{(n_e)_{Al}}\ \frac{\sigma_e+\tau_e}{\sigma_e}\,.$$

Now, our Pb-counter and Al-counter of wall thickness 0.22 mm and 0.92 mm have practically the same mass per square cm of the wall (mass ratio=1.015). If the mass absorption coefficients of the ejected electrons in lead and aluminium be equal,

(5) Gray, Proc. Camb. Phil. Soc. vol. 27, p. 103 (1931).

we should also have their counting efficiencies towards such electrons nearly equal and the above raito should be equal to N_{Pb}/N_{Al} provided no particles were ejected from the nuclei. For $\lambda=6.6$ x. u. we have, in fact,

$$\frac{N_{Pb}}{N_{Al}}=0.97, \quad \frac{(n_e)_{Pb}}{(n_e)_{Al}} \frac{\sigma_e+\tau_e}{\sigma_e}=0.97,$$

showing the equality of the mass absorption coefficients of the ejected electrons in lead and aluminium, which in turn indicates the fact that the effect of nuclear scattering towards ejected electrons is not very important for the above wave-length (though the close agreement may be accidental).

(c) We can extend the above calculation to other wave-lengths. But here only the relative values are to be compared in order to use the data with the thicker counters. When no nuclear effect exists, again we should expect N_{Pb}/N_{Al} to be proportional to $(\sigma_e+\tau_e)/\sigma_e$ or $(\sigma+\tau)_{Pb}/\sigma_{Pb}$. To render the comparison easy, N_{Pb}/N_{Al} and $(\sigma+\tau)_{Pb}/\sigma_{Pb}$ are multiplied by k and k' so that the two ratios are equal to 1 at $\lambda=6.6$ x. u. The result is listed below.

Table II.

λ	4.7	6.6	9.35	12.1
σ_{Pb}	.337	.410	.495	.563
τ_{Pb}	.035	.063	.118	.199
$k'(\sigma+\tau)_{Pb}/\sigma_{Pb}$	.96	1.00	1.07	1.17
$k\ N_{Pb}/N_{Al}$	$1.16\pm.04$	$1.00\pm.00$	$1.11\pm.08$	$1.23\pm.08$

It is seen that the agreement is within the limit of experimental error every-where with the exception at $\lambda=4.7$ x. u., where particles ejected from Pb-nuclei are to be expected.

(d) The ratio N_{Pb}/N_{Al} was also determined with a beam of RaC′ γ-rays filtered through 6 cm lead and with a beam of ThC″ γ-rays filtered through 3 cm lead. It was found that the ratio N_{Pb}/N_{Al} for γ-ray of ThC″ is about 12% greater than that for γ-rays of RaC′. The wave-lengths and intensities of the 3 intense components of RaC′ γ-rays filtered through 6 cm lead are shown below:

$\lambda=5.6$	6.9	10.9
$I=2.82$	11.3	4.13

An approximate calculation can be made which will show that the result here obtained is in fair agreement with that obtained by using primary γ-rays of ThC″ and the scattered beams.

(e) During the preparation for this publication several papers[6] concering this subject have been published by Anderson and Neddermeyer, Chadwick, Blackett and Occhialini, and Curie and Joliot. By the use of Wilson's expansion chamber, they have succeeded in observing positive electrons and occasionally pairs of electrons, one positive and one negative, ejected from a Pb-plate by the hard γ-rays. It was first suggested by Blackett and Occhialini[7] that a pair of electrons might be created by the conversion of a γ-ray of high energy in the strong field of the nucleus and this view is in accord with Dirac's theory of electrons.[8] According to Dirac's theory, the process of creation of a positive and a negative electrons results from the excitation by the hard radiation, of a negative electron initially in a negative energy state ($mc^2<0$) to a positive energy state, the unoccupied negative energy state then behaving as a positive electron. When the extra number of particles observed in the Pb-counter in our experiment is regarded as being positive and negative electrons created in such process, the disintegration hypothesis originally assumed might be not necessary.

(f) As is calculated in (b), the ratio N_{Pb}/N_{Al} for $\lambda=4.7$ x. u. without considering the nuclear interaction would be 4% lower than that for $\lambda=6.6$ x. u. The extra counts due to nuclear interaction in the Pb-counter therefore amount to 17% of the

(6) Anderson and Neddermeyer, Phy. Rev. vol. 43, p. 1034 (1933), vol. 44, p. 406 (1933); Chadwick, Blackett and Occhialini, Nature, vol. 131, p. 473 (1933); Curie and Joliot, Comptes Rendus, vol. 196, p. 1105 (1933); Chadwick, Proc. Roy. Soc. A, vol. 142, p. 1 (1933).

(7) Blackett and Occhialini, Proc. Roy. Soc. A, vol. 139, p. 669 (1933).

(8) Dirac, Proc. Roy. Soc. A, vol. 126, p. 360 (1930), vol. 133 p. 60 (1931).

total counts, while for the same wave-length the nuclear absorption of lead is about 22% of the total absorption.[9] Hence the two magnitudes are quite in conformity.

(9) Science Reports loc. cit.