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SCATTERING OF HARD γ-RAYS

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ABSTRACT

Measurements have been made on the scattering of γ-rays from Th C″ by Al and Pb. For Al the scattering is, within experimental error, that predicted by the Klein Nishina formula. For Pb additional scattered rays were observed. The wavelength and space distribution of these are inconsistent with an extranuclear scatterer, and hence they must have their origin in the nuclei.

INTRODUCTION

IN A previous study of the absorption coefficient of hard γ-rays in various elements,[1] it was found that the absorption coefficient of light elements was predicted fairly well by the Klein-Nishina formula which assumes that the removal of the energy from the primary beam is entirely due to Compton scattering of the extranuclear electrons. For heavy elements, however, the experimental value was much larger than was to be expected from the Klein-Nishina formula or any other. Two causes can be suggested to explain this additional absorption. (a) It may be an extranuclear phenomenon due either to an ordinary photoelectric absorption or a breakdown of the Klein-Nishina formula for Compton scattering in these elements. (b) It may also be a nuclear phenomenon, such as the scattering by particles inside the nucleus or any other nuclear absorption (like the excitation or the photoelectric effect occurring there). In an attempt to obtain more information about these questions, a study of the scattered rays has been made.

EXPERIMENTAL RESULTS

In this experiment, γ-rays from Th C after being filtered through 2.7 cm of Pb were used as the primary beam. Al and Pb were chosen as the representatives of the light and the heavy elements. The scatterer was set about 50 cm from the source, which was contained in the same lead cylinder used in the previous experiment. The Al scatterer was $11\times8\times2.5$ cm in size, the Pb scatterer was approximately equivalent to this in total number of

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[1] Chao, Proc. Nat. Acad. Sci. **16**, 431 (1930).

electrons. The scattered rays were studied by means of an ionization chamber with 20 atmospheres pressure at a distance of about 20 cm from the scatterer. The work consisted of three parts.

(a) The comparison of the intensities scattered from Al and Pb is shown in Table I. Here $\lambda+\Delta\lambda$ gives the wave-length of the scattered rays according to Compton's fomula, μ'_{Al} and μ'_{Pb} are their absorption coefficients in Al and Pb respectively. $S_{\mathrm{K\&N}}$ gives the theoretical intensity distribution, expressed in terms of the number of the scattered quanta, according to the Klein-Nishina formula for $\lambda=4.85$ x.u. (i.e. $\alpha=5$), S_{D} gives that according to Dirac's old formula. S_{Al} is the observed distribution of quanta scattered by Al. Corrections are made for the absorption in the scatterer of both the primary and scattered rays and for the change of efficiency of ionization for different wave-lengths (the latter correction is made by assuming that the efficiency of ionization is proportional to the absorption coefficient in light elements). By comparing $S_{\mathrm{K\&N}}$ and S_{Al}, we see that the agreement between the theory and the experiment is indeed fairly good.

Now, since we are mainly interested in the comparison of the scattered intensities from Al and Pb, a set of measurements was made which gives directly the ratio of the ionization currents due to the scattered rays from the two scatterers. If the scattered rays from Al and Pb are of the same hardness, the ionization current i should be proportional to the energy E of the scattered rays passing through the ionization chamber. In the table, $(E_{\mathrm{Pb}}/E_{\mathrm{Al}})_1$ is calculated by assuming that the scattered intensity at a definite angle is proportional to the number of the extranuclear electrons per cc, i.e. the value predicted by the Klein-Nishina formula. Here again correction is made for the absorption in the scatterer of both the primary and scattered rays, the variation of the ratio for different angles being due to this correction $(i_{\mathrm{Pb}}/i_{\mathrm{Al}})$ is the observed ratio of the ionization currents. It is to be noted here that in the forward direction $(i_{\mathrm{Pb}}/i_{\mathrm{Al}})$ is fairly close to $(E_{\mathrm{Pb}}/E_{\mathrm{Al}})_1$, but in the backward direction $(i_{\mathrm{Pb}}/i_{\mathrm{Al}})$ is much greater than $(E_{\mathrm{Pb}}/E_{\mathrm{Al}})_1$ and is even greater than $(E_{\mathrm{Pb}}/E_{\mathrm{Al}})_2$ which is calculated by assuming that the scattered intensity at a definite angle is proportional to the absorption coefficient at the scatterer. From this fact we can infer that in the case of Pb, beside the normal Compton scattering there is still a kind of anomalous scattering. This anomalous scattering, in fact, gives about three times as much ionization current as the normal scattering does at $\theta=135°$, as shown at the end of Table I.

TABLE I. *Absorption coefficient of the primary rays,* $\mu_{\mathrm{Al}}=0.109$, $\mu_{\mathrm{Pb}}=0.515$. *Mean wave-length, deduced from* $\mu_{\mathrm{Al}}=5.2$ X.U.

Angle of Scattering	22.5°	35°	55°	90°	135°
$\lambda+\Delta\lambda$	7.0	9.6	15.5	29.4	47
μ'_{Al}	.129	.153	.193	.25	.29
μ'_{Pb}	.61	.74	1.02	2.0	4.8
$S_{\mathrm{K\&N}}$		1	.493	.249	.180
S_{D}		1	.277	.061	.037
S_{Al}		1	.504	.254	.188
$(E_{\mathrm{Pb}}/E_{\mathrm{Al}})_1$	.70	.72	.70	.57	.38
$(i_{\mathrm{Pb}}/i_{\mathrm{Al}})$	.695	.75	.80	.96	1.44
$(E_{\mathrm{Pb}}/E_{\mathrm{Al}})_2$	.965	.995	.97	.80	.53

(b) The hardness of the scattered rays is shown in Table II. Here i_0 is the ionization current due to the initial scattered rays, i' is that due to the scattered rays after passing through a Pb-absorber of 0.68 cm thickness. From Table II we see that the hardness of the scattered rays from Al agrees very well with that which is to be expected for ordinary Compton scattering, but the scattered rays from Pb are harder than is predicted by the simple theory for these angles. Later on, a separate investigation of the scattered rays from Pb was made with a thicker Pb-scatterer (1.36 cm) and less filtering (1.4 cm) of the primary rays in order to obtain greater intensity. The result of this investigation is shown in Table III. Here, the anomalous scattered rays seem to be almost monochromatic to the limit of accuracy of the present experiment.

TABLE II.

Angle of Scattering	90°		135°	
Scatterer	Al	Pb	Al	Pb
$(\mu'_{\mathrm{Pb}})_{\mathrm{cal.}}$	2.0		4.8	
i_0	310	297	75	108
i'	69	101	4	43
$(\mu'_{\mathrm{Pb}})_{\mathrm{obs.}}$	2.2	1.6	4.3	1.4

TABLE III.

Thickness of Absorber		0		68		1.36		204 cm
90°	i	894		308		109		45
	μ'_{Pb}		1.6		1.5		1.3	
135°	i	448		151		55		19
	μ'_{Pb}		1.6		1.5		1.6	

(c) Assuming the absorption coefficient of the anomalous scattered rays to be 1.5 in Pb (It is probably too low owing to the fact that the absorbers were set at a distance of only 4 to 5 cm from the ionization chamber.), we can deduce the wave-length of these rays to be 22.5 X.U. From the result of Table I, we can now compute the intensity distribution of the anomalous scattered rays as given in Table IV. Since the absorption coefficient of the scattered rays plays a very important rôle in such calculations and the ratio of the anomalous scattered intensity to the normal scattered intensity is very small in the forward direction, these values can only give a rough idea.

TABLE IV. *Intensity distribution of the anomalous scattered rays.*

Angle	35°	55°	90°	135°
Intensity Distribution	.05	.06	.07	.08

DISCUSSION

In view of these results we shall consider the different possible causes as to the origin of the anomalous scattering.

(*a*) *Extranuclear hypothesis*: Under this heading we can include the following subdivisions. (1) The ordinary photoelectric effect. The anomalous scattering can not be explained in this way because, first, it should be very small theoretically, and, secondly, the scattered radiation is much harder than the K-radiation of Pb, which is the hardest that can be obtained from the change of the extra-nuclear electronic configuration. (2) The extranuclear Compton scattering. Since the intensity distribution of Al-scattering agrees fairly well with the Klein-Nishina formula and the intensity distribution of Pb-scattering is widely different, the anomalous scattering does not comply with this hypothesis, Still more important is the fact that the change of the wave-length is much smaller than is predicted for Compton scattering, this prediction is independent of any intensity formula. One might expect the scattering of the tightly bound electrons of inner shells to be different from the ordinary Compton scattering at first thought, but it does not seem adequate for the explanation in considering the fact that we have 2.7×10^6 volts photon against 7.5×10^4 volts for the binding energy of the K-electrons of Pb. Furthermore the change of wave-length found experimentally is not to be expected in the scattering of the tightly bound extranuclear electrons.

(*b*) *Nuclear hypothesis*: Under this heading we have again (1) the scattering process, the mechanism of which is not yet well known, (2) the re-emission after photoelectric absorption or nuclear excitation. Since inside the nucleus the separation of energy levels is greater, the change of wave-length can be accounted by either process. But in considering the fact that the intensity distribution of the anomalous rays is almost uniform in different directions, it seems more probable that it originates from the re-emission process.

Although the final solution of this problem is not yet reached, nevertheless from the present experiment it is fairly evident that the additional absorption as well as the anomalous scattering of hard γ-rays by heavy elements, at least Pb, originates in the nucleus.

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