Photo-Fission of Uranium and Thorium Produced by the \( \gamma \)-Rays of Lithium and Fluorine Bombarded with High Speed Protons.


(Read April 5, 1941)

After a number of failed attempts made by several workers, the fission effect of heavier nuclei caused by the irradiation of \( \gamma \)-rays was successfully carried out recently by the members of Westinghouse Research Laboratories. They announced that the cross-sections for the photo-fission produced by the \( \gamma \)-ray of \( F(p \gamma) \) reaction was found to be 
\[ \sigma_{\text{U}} = (3.5 \pm 1.0) \cdot 10^{-27} \text{ cm}^2, \]
and 
\[ \sigma_{\text{Th}} = (1.7 \pm 0.5) \cdot 10^{-27} \text{ cm}^2, \]
respectively, while that of the photo-fission produced by the \( \gamma \)-ray from \( \text{Li}(p \gamma) \) reaction was presumed to be of the same order of magnitude. The observation with this 17 MeV \( \gamma \)-ray, however, could not be satisfactorily worked out for the reason of the feeble intensity of the \( \text{Li}(p \gamma) \) \( \gamma \)-ray used.

Meanwhile, the present writers have been, also, working for the same observation by mainly using the \( \gamma \)-ray of \( \text{Li}(p \gamma) \) as well as that of \( F(p \gamma) \). We have ascertained that the phenomena of photo-fission, as was observed in Westinghouse, really exist. The fission cross-sections of uranium and thorium nuclei for various \( \gamma \)-ray quanta have been found to be
\[ \sigma_{\text{U}} = 16.7 \cdot 10^{-27} \text{ cm}^2 \text{ for } \text{Li}(p \gamma) \gamma \text{-ray}, \]
\[ \sigma_{\text{Th}} = 7.2 \cdot 10^{-27} \text{ cm}^2 \text{ for } \text{Li}(p \gamma) \gamma \text{-ray}, \]
and
\[ \sigma_{\text{RaC}} = 2.2 \cdot 10^{-27} \text{ cm}^2 \text{ for } F(p \gamma) \gamma \text{-ray}, \]
respectively.

The present paper is going to give a short account of our experiments. Now the proton beam of about 70 \( \mu \)A* was directed on the

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* The whole equipment is a modification of Cockcroft-Oliphant and Rutherford type, which is capable to operate up to about one million volts driving the ion current of 500 micro-amperes and more.
target of metallic lithium or LiF-powder coated on the bottom of a thin brass tube 0.25 mm thick. It was focussed to a spot of 3-1 mm in diameter. The number of $\gamma$-ray quanta was counted by a specially constructed Geiger-Müller counter of lead wall 6.5 mm thick, the inner diameter and the length of working part of which is 2 cm and 2 cm respectively. The reason of selecting lead for the material and 6.5 mm for the thickness is simply that the lead wall of this thickness can just prevent those electrons of energy of 17 MeV and less from entering into the counter which may be expelled from the surrounding materials by the $\gamma$-rays of Li($p\gamma$) and F($p\gamma$) reaction. The counting efficiency of this counter was calculated by M. Sonoda taking the knowledge of electron-pair production and that of the Compton effect etc. in mind, and namely

$$28.2\%$$ for the $\gamma$-ray of 54 me$^2$ energy

and

$$9.0\%$$ for the $\gamma$-ray of 12 me$^2$ energy.

Since the above values of counting efficiency were found to be tolerably adequate by some experimental justifications, they are presumably used, at present, in the computation for the determination of the absolute number of $\gamma$-ray quanta concerned.

In actual measurements, the counter was placed at a point 46.7 cm distant from the target and was usually shielded by a lead cylinder 6.6 mm thick. The natural background of the counter was 14.00 min. in average. Another brass counter of the same dimension was used for the standardizing purpose in some cases, and it was always provided with lead shielding 10 mm thick.

The practical absorption factor of the lead cylinder covering the counter was carefully observed for both of the rays of 17 MeV and 6.3 MeV, and namely

$$\mu_{\gamma}(\text{Pb Cylinder}) = 0.53 \text{ cm}^{-1}$$

and

$$\mu_{\gamma}(\text{Pb Cylinder}) = 0.40 \text{ cm}^{-1}.$$  

The actual readings of the counter were corrected thereby in computing the absolute number of $\gamma$-ray quanta emitted from the target.

Now, a small ionization chamber for observing the fission fragments was placed beneath and near the target as shown in the annexed figure. 40 mg of greenish gray powder of U.O$_2$ was coated on the inner surface (10.18 cm$^2$ in area) of the ionization chamber, the ion collector of which was directly connected to the grid of the first valve of a linear amplifier. After it was once adjusted to count $\alpha$-particles in order, the sensitivity of the counter was usually so reduced that no kicks due

to $\alpha$-particles (of uranium) could be observed on the fluorescence screen of a cathode-ray oscillograph, one of whose deflecting pole-plates was coupled to the plate circuit of the power valve of the amplifier. A rarer number of small pulses probably due to coincident $\alpha$-particles of uranium were found to be observed as kicks of few millimeters, while those due to fission fragments were always found to be about 3 cm, showing their characteristic feature. No one could, accordingly, misscount them. Since the thickness of uranium oxide is considered to be about 1 cm (2) air equivalent for the fission fragments, the fission fragments of uranium produced by the 17 MeV $\gamma$-ray are, for the most part, to be taken as nearly homogeneous and the range is estimated to be about 1.5 cm of air because the depth of the ionization chamber is 5 mm. Now we observed the number of kicks due to fission fragments against the intensity of the $\gamma$-ray emitted from the target for the various voltages driving the bombarding ions. It was found that the fission activity was so distinctly parallel with the resonantly emitted $\gamma$-ray that no ambiguity was there for the observing phenomena.

Since the yield of the $\gamma$-ray from the target diminished from time to time, we could also ascertain that the fission activity varied as the intensity of the $\gamma$-ray.

Now the results obtained in this way for uranium exposed to Li ($p $-$ \gamma$) $\gamma$-ray are shown in the table I.

<table>
<thead>
<tr>
<th>Target</th>
<th>$V$</th>
<th>$\gamma$</th>
<th>$N_0$</th>
<th>$n_\gamma$</th>
<th>$f_\gamma$</th>
<th>$\sigma_{\text{U}(17)}$</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li (Metal)</td>
<td>510 KV</td>
<td>820.3 min</td>
<td>85.5 $\times 10^9$</td>
<td>$1.35 \times 10^7$ $\text{min}^{-1}$</td>
<td>17.3 $\text{min}^{-1}$</td>
<td>$1.35 \times 10^{-20}$ $\text{cm}^2$</td>
<td>10 $\sim$ 15%</td>
</tr>
</tbody>
</table>

$V$: Voltage driving ions.

$\gamma$: $\gamma$-ray counted (Natural background subtracted).

$N_0$: Number of U nuclei exposed to $\gamma$-ray

$n_\gamma$: Number of $\gamma$-ray quanta falling on $N_0$.

$f_\gamma$: Number of fission fragments observed.

$\sigma_{\text{U}(17)}$: Fission cross-section $= f_\gamma / N_0 n_\gamma$. 
The fission effect of the 17 MeV γ-ray on thorium nucleus was similarly observed, and namely in comparison with that on uranium nucleus in the same experimental conditions as possible.

We observed 5.3 fission fragments per minute from 40 mg of ThO₂ when the γ-ray counter counted 927.2/min, while 13.0 of fission fragments were observed per minute from 40 mg of U₃O₈ when the γ-ray counts amounted to 1038.9/min.* Since \( N_{Th} = 9.1 \times 10^{19} \) and \( N_{U} = 8.5 \times 10^{19} \), we obtain \( \sigma_{U} : \sigma_{Th} = 2.3 \). Then, by using the value \( \sigma_{U}(17) = 16.7 \times 10^{-27} \text{cm}^2 \), we have \( \sigma_{Th}(17) = 7.2 \times 10^{-27} \text{cm}^2 \) for the γ-ray of 17 MeV energy.

It is interesting to note that the ratio varies very little with the energies of the irradiating quanta, since the result for \( F(p \cdot \gamma) \) γ-ray observed by Haxby, Shoupp, Stephens and Wells was announced to be \( \sigma_{U/2} : \sigma_{Th} = 2.0 \).

A second series of experiments were carried out, in which the fission activity was taken against the intensity of γ-rays emitted from thick target of LiF powder for various driving voltages of bombarding protons up to 520 KV, so that we could not only determine the fission cross-section of uranium nucleus for \( F(p \cdot \gamma) \) γ-ray but also roughly check the value for Li(p · γ) γ-ray at once, since we had previously measured the relative intensity of \( F(p \cdot \gamma) \) γ-ray (6.3 MeV) related to the first resonance voltage at 330 KV and that (6.3 MeV)** associated to the second one at 480 KV, as

\[
F_{1}(p \cdot \gamma) : F_{2}(p \cdot \gamma) = 1.0 : 0.5,***
\]

Thus from the observed values,

<table>
<thead>
<tr>
<th>Driving voltage</th>
<th>γ-ray counted</th>
<th>Number of fission observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>310 KV</td>
<td>231/min.</td>
<td>1/30 min.</td>
</tr>
<tr>
<td>400 KV</td>
<td>( F_{1} = 4510 \text{/min.} )</td>
<td>3/50 min.</td>
</tr>
<tr>
<td>500 KV</td>
<td>( (F_{1} + F_{2} + L) = 8667 \text{min.} )</td>
<td>8.8/min.</td>
</tr>
</tbody>
</table>

We get table II.

The value of the cross-section here obtained is fairly small compared

* In this case, the experimental condition was not so good as in the case of Table 1, the γ-ray source was to be taken as broadened in the target tube and affected the solid angle subtended to the fission substance diminishingly. We can, therefore, only compare their activities but not directly compute the absolute values of their cross-sections.

** By the absorption measurement for lead, it was found that the energy of γ-ray associated to 480 KV is likewise 6.3 MeV.

*** According to Streib, Fowler and Lauritsen(4) this value is about 18 : 5 but we got 1 : 0.5 from the careful observations for thin targets as well as for thick ones.

with the value $3.47 \times 10^{-27} \text{cm}^2$ obtained by H.S.S. and W.\(^{(2)}\). Since, however, the observed fission activity for $F(p\gamma)\gamma$-ray was weak in our experiment, the accuracy of the value is not to be taken sufficiently high. It is, moreover, to be noticed that, in order to estimate the absolute number of $\gamma$-ray quanta, the efficiency of the lead counter was taken, by theoretical calculations, to be $9.0\%$ in our experiment, while that of the counter used by those workers had been assumed to be $2\%$ without giving any detail. It is therefore to be taken that those two values are rather in good agreement. If we take, for the present, $\sigma_{F1} = 2.1 \times 10^{-27} \text{cm}^2$, and $\sigma_{F2} = 16.7 \times 10^{-27} \text{cm}^2$, as before described, the ratio $\sigma_{F1}:\sigma_{F2}$ becomes 7.6 : 1 and, therefore, we see that the fission cross-section is approximately proportional to $(hv)^2$ of the irradiating $\gamma$-rays. This result is obviously different from the theoretical consideration made by Weisskopf\(^{(2)}\) who claimed it ought to vary with $(hv)^3$.

Finally, we observed the effect of $\gamma$-rays from 50 mg of Ra on uranium, but in vain. We counted, indeed, one fission in one case, after the patient observation of 2 hours, but this order of count may be anticipated as the result of the fission activity caused by neutrons emitted from the $\gamma$-ray source.\(^{(5)}\)

It is therefore to be taken that there exists, for the photofission activity of uranium, a threshold value of $\gamma$-ray energy between 6 MeV and 22 MeV at least. Though the number of the observed points for different values of $\gamma$-ray energies is very small, we are suggested by the results obtained in the present experiments that the cross-section of photo-fission effect would be presumably formulated into

$$\sigma = \sigma_0 \left( \frac{hv}{h_0} \right)^{\alpha} \left( 1 - \left( \frac{hv}{h_0} \right)^{\alpha} \right),$$

in which the value of the index $\alpha$ is considered adequately to be greater than 2; the value of $\sigma$ varies little with $\alpha$ and is about $1.45 \times 10^{-28} \text{cm}^2$ for $\alpha = 4$, while the energy of the threshold frequency is, then, taken to be about $h_0 = 3.0 \text{MeV}$.

At any rate, further observations are now in progress and the range

On the Scattering of Mesons by Nuclear Particles.

By Yasutaka Tanikawa and Hideki Yukawa.

(Read Nov. 26, 1940)

§ 1. Introduction and Summary.

Although the meson theory succeeded on the whole in interpreting the structure of atomic nuclei as well as the nature of cosmic ray particles, the theory in the present form meets with a lot of difficulties, when the comparison with the experiment is made in detail. As to the origin of these difficulties, the opinions of many authors are more or less at variance with each other. It is no doubt, however, that the shortcoming of the present theory is twofold. On the one hand, we cannot yet find out a general method of relativistic quantum mechanics, which is free from any divergence difficulty, and it is very probable that the phenomena involving the creation and annihilation of mesons are entirely outside of the limit of applicability of the present method of quantization as suggested by Heisenberg.

On the other hand, we are not sure whether the specific assumptions made at present as to the nature of different kinds of elementary particles are all correct or not. The latter point is of particular importance in the case of the meson and we have to investigate one

(1) Heisenberg, ZS. f Phys. 110 (1938), 251.