Fission of U, Th, Bi and Tl Induced by High Energy γ-Quanta

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The photofission yields of U^{238}, Th^{232}, Bi^{209} and $Tl^{204,206}$ have been measured with an ionization chamber at bremsstrahlung maximum energies from 80 to 250 mev. The photofission effective cross sections computed by the total spectrum method rapidly increase from ~80 mev and at 250 mev reach a value of (220 ±80) mb for U, (80 ±30) mb for Th, (4.7 ±0.6) mb for Bi and (1.6 ±0.2) mb for Tl. The energy dependence of the cross sections is the same for all four elements and, above 150 mev, is similar to the energy dependence of the total cross section for photoproduction of neutral and charged mesons.

INTRODUCTION

ALL the experimental results on photofission reactions attest to the fact that for photons with energies 10 to 30 mev, γ-ray absorption in nuclei takes place through a dipole mechanism. The measurement of photoneutron yields[1,2] and photostars[3,4] showed the rise in the effective cross section for photon energies greater than 100 mev. An attempt has been made[4] to explain the observed increase in the cross section for formation of stars above 150 mev by reabsorption of mesons in nuclei. On the basis of the concept of reabsorption, a conclusion has been reached[5] that within the nucleus mesons , because of their nature, must be absorbed as soon as they are created, and that virtual mesons must give an appreciable contribution, in consequence of which the "meson" part of the photofission cross section will extend in the region of photon energies less than the threshold for meson production.

The study of the dependence of the fission cross section of heavy nuclei on the photon energy up to $\hbar\nu \sim 300$ mev[6-10] has given in a general way analogous results. However, while in the region of the giant resonance the energy dependence of the photofission cross section has been studied sufficiently thoroughly, fairly complete information is not available for $\hbar\nu > 100$ mev. Because of this, there was interest in investigating this dependence more fully for a number of heavy nuclei at high photon energies. This work is devoted to this problem.

DESCRIPTION OF THE EXPERIMENT

In our experiments, carried out on the synchrotron of the Physics Institute of the Academy of Sciences , USSR, we measured the dependence of the photofission yield of the nuclei of U^{238}, Th^{232}, Bi^{209} and $Tl^{203,205}$, on the maximum energy of the bremssrahlung radiation. The geometry of the experiments is shown in Fig. 1.

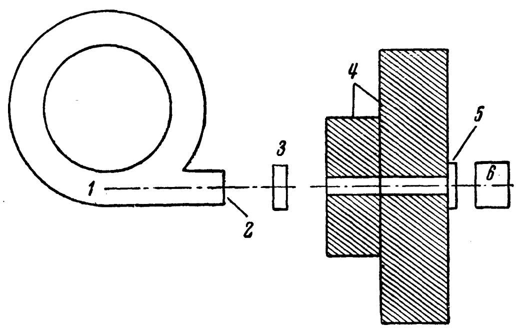

FIG. 1. Experimental Set-up. 1—synchrotron target; 2—aluminum disk covering the window in the vacuum chamber; 3—thin-walled ionization chamber; 4—lead shielding; 5—holder for the copper foil; 6—ionization-chamber registering fission events.

The beam of γ-quanta, leaving the vacuum chamber of the synchrotron through a window covered with a thin aluminum disk, passed through a lead collimator of 50 mm diameter behind which was placed a pulse ionization chamber, registering fission events. A thin-walled ionization chamber placed in front of the collimator was used for measurements of the relative intensity of the beam of γ-quanta.

The characteristic property of work with the accelerator is the presence of a strong electron background which, to a considerable extent, makes it more difficult to carry out the measurements. In order to decrease the background ionization, produced in the sensitive volume of the chamber by secondary electrons, the electrodes were made of thin aluminum foils and the windows in the housing of the chamber were closed with an organic layer of 30 μ thickness. Nevertheless, reliable compensation for the background was attained only when the duration of the photon beam was increased to 500 μ sec for maximum energies of 250 and 200 mev and to 300 μ sec for lower energies. The chamber was filled with chemically pure argon to a pressure of 250 mm of Hg.

The targets of the elements being investigated were prepared in the form of thin U_3O_8 and ThO_2 layers[7] and metallic (layers) of Bi and Tl[11] deposited on aluminum backings of 30 μ thickness and of 40 mm diameter. Since the diameters of the chamber

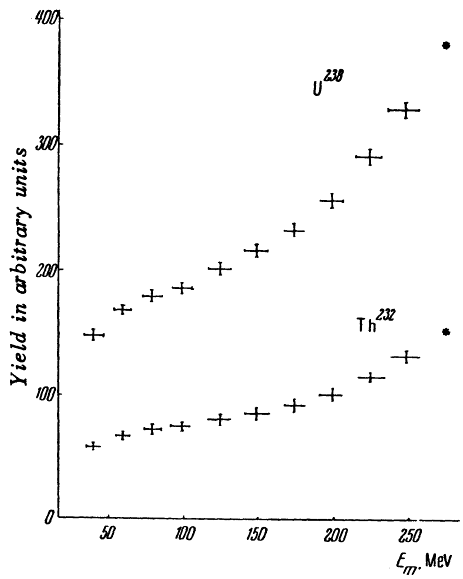

FIG. 2. Dependence of the photofission yield of U^{238} and Th^{232} on the maximum energy of the bremsstrahlung radiation (* are the values obtained by extrapolating the curves to $E_m = 275$ mev).

electrodes were 75 mm, the fragments emitted from the edge of the target were not counted.

In the determination of the dependence of the photofission yield of thorium on the maximum energy of the bremsstrahlung radiation, the intensity of the γ-quanta beam was measured from the yield of the reaction $Cu^{63}(\gamma, n)Cu^{62}$ [12] in a copper target irradiated at the same time as the thorium target. Corrections dealing with non–uniform intensity during irradiation were introduced in the experimental value of the yield of the 10–minute activity of the Cu^{62} nuclei. The photofission yields of uranium, bismuth and thallium were measured relative to the yield for thorium. From the curves of the dependence of the photofission yields on the maximum energy of the bremsstrahlung radiation, the effective cross sections were calculated as a function of photon energy by the total spectrum method. Moreover the effective cross section for the reaction $Cu^{63}(\gamma, n)Cu^{62}$ for photon energies greater than 30 mev was taken to be zero. The agreement of the results on the photofission of Bi^{209} obtained in this work with the results obtained by Ref. 10, in which the intensity of the γ-quanta was measured with a threshold chamber, shows that it is possible to neglect the possible existence of the tail of the cross section of this reaction.

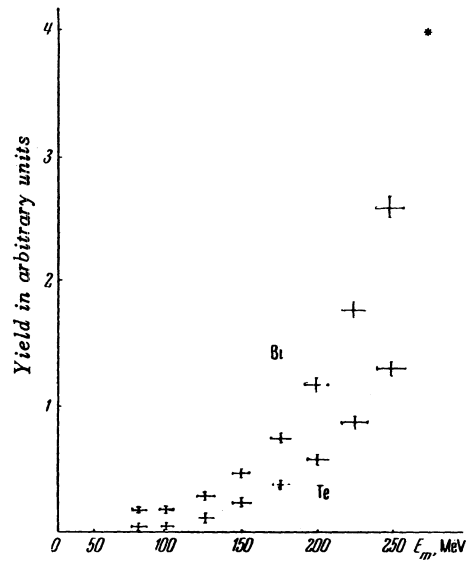

FIG. 3. Dependence of the photofission yield of Bi^{209} and $Tl^{203,205}$ on the maximum energy of the bremsstrahlung radiation.

Figures 2 and 3 show the dependence of the photofission yield, proportional to

$$\int_{E_p}^{E_m} \sigma_f(w)\, \eta(w, E_m)\, dw,$$

on the maximum energy of the bremsstrahlung radiation. The energy dependence of the photofission cross section is presented in Figs. 4–7.

The value of the average cross section

$$\int_5^{40} \sigma_f(w)\, \eta(w, 40)\, dw \Big/ \int_5^{40} \eta(w, 40)\, dw$$

in the 5 to 40 mev interval for U^{238} is equal to 38 mb which is not very different from the value of 44 mb which can be obtained from the results of Ref. 13.

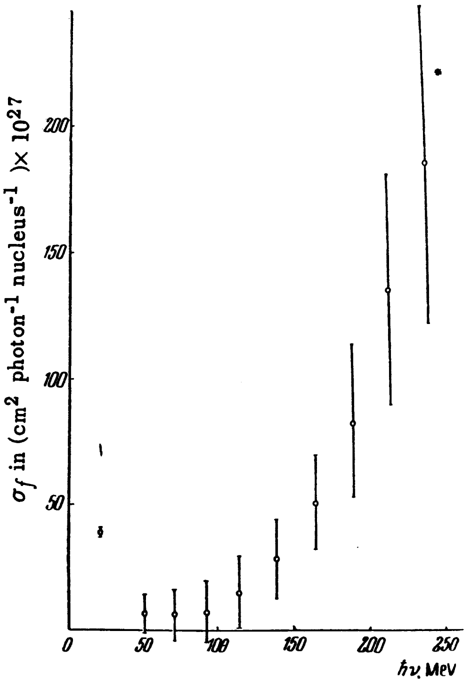

FIG. 4. Photofission cross section of U^{238} (*denotes the value obtained by extrapolating the curve to an energy $\hbar\nu = 250$ mev).

However it turns out to be for example one and a half times smaller than the values obtained from Refs. 8 and 14. The ratio of the photofission yields of Bi^{209} and U^{238} for a maximum energy of 85 mev, equal to 0.0009, coincides with the result of Ref. 15. The ratios of the photofission yields of U^{238}, Th^{232}, Bi^{209} and $Tl^{203,205}$ for a maximum energy of 275 mev[9] coincides with the ratios of the yields extrapolated to this energy from the present work. The energy dependence and the magnitude of the photofission cross section of Bi^{209} are in good agreement with the results of Ref. 10.

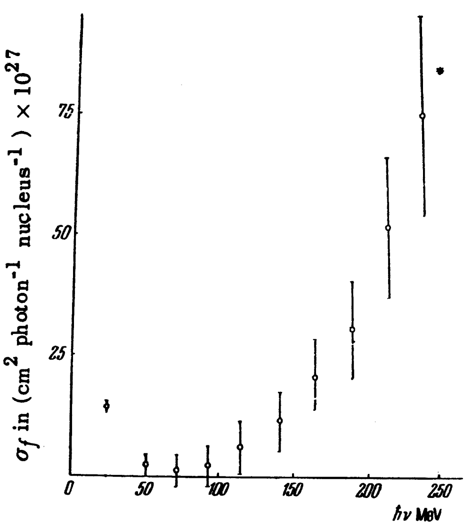

FIG. 5. Photofission cross section of Th ^{232}.

While the errors in the cases of uranium and thorium are large, nevertheless it is clear that the photofission cross sections for all four elements rise quickly with an increase in the energy of the photons starting for example at 80 mev and attaining values of (220 ± 80) mb for U^{238}, (80 ± 30) mb for Th^{232}, (4.7 ± 0.6) mb for Bi^{209} and (1.6 ± 0.2) mb for $Tl^{203,205}$ by 250 mev. Figure 8 shows the course of the photofission cross sections of these nuclei as well as the sums $\sigma(\pi^0) + \sigma(\pi^+)$ of the production cross section for neutral and charged mesons from free protons, normalized at a photon energy of 250 mev. As can be seen, the course of the photofission cross section in the region of 80 to 250 mev is the same for all four elements and above 150 mev coincides with the course of the total production cross section of neutral and charged mesons.

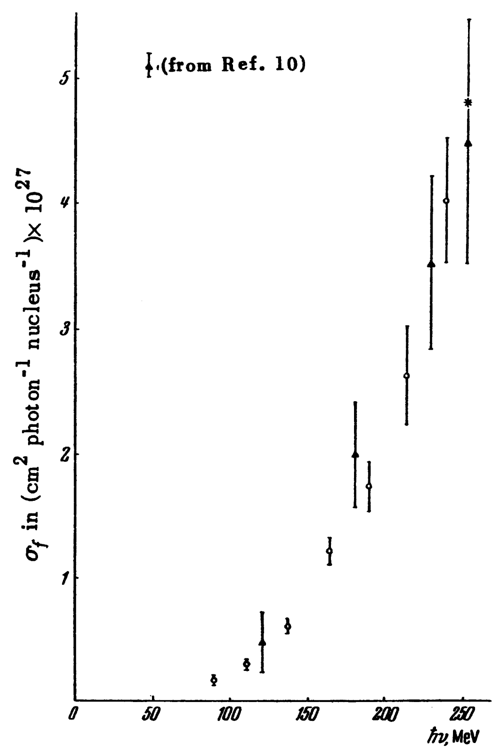

FIG. 6. Photofission cross section of Bi^{209}.
▲: data of Ref. 10

DISCUSSION OF THE RESULTS

The photofission cross section can be presented in the form

$$\sigma_f = \sigma_a \Gamma_f / \Sigma\Gamma,$$

where σ_a is the absorption cross section for the photon in the nucleus, and $\Gamma_f / \Sigma\Gamma$ is the relative fission probability which is equal to 0.2 to 0.4 for uranium[14,17] and which is 2.5 to 3 times smaller for thorium.[17] Because of this, the photofission cross section can rise because of the increase of $\Gamma_f / \Sigma\Gamma$ a maximum of 5 times in the case of uranium and of 10 times in the case of thorium.

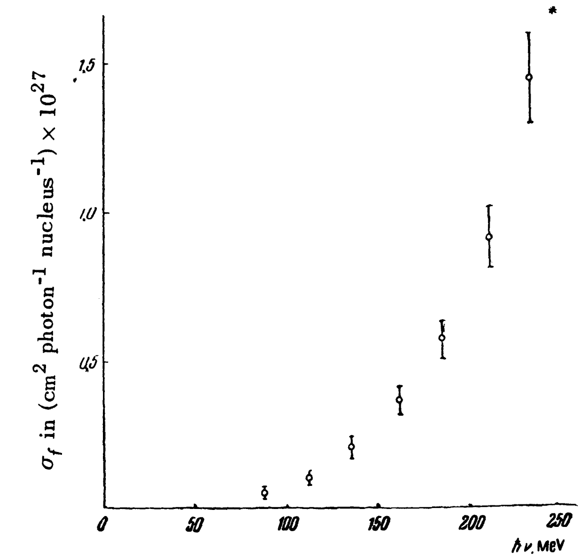

FIG. 7. Photofission cross section of $Tl^{203,205}$.

However, the experimental values of the photofission cross section of these elements increase more than 20 times from 80 to 250 mev. Moreover, a value of also ~ 0.4[18] was obtained for $\Gamma_f/\Sigma\Gamma$ in experiments on the fission of U^{238} by slow π^-–mesons. This shows that for a wide region of excitation energy the relative fission probability of U^{238} remains practically constant. The non–emissive character of the fission of U^{238} is confirmed by the results of experiments on the study of the mass spectra of fragments.[13,19] The curves obtained on the distribution of fragments as a function of mass testifies to the fact that for γ–quanta in the energy region of 10 to 300 mev, 3 to 4 neutrons are emitted in each fission event. Thus, at least in the case of U^{238}, the rise of σ_f in the interval of photon energy of 80 to 250 mev depends only on the increase of σ_a.

The fact that the photofission cross sections of all four elements start to rise at the same photon energy and change in the same way up to $h\nu = 250$ mev shows, in our opinion, that for Th^{232}, Bi^{209} and $Tl^{203,205}$ the rise of σ_f depends also on the increase in σ_a. The emissive character of fission, observed when Bi^{209} was irradiated with neutrons[11,20] and γ–quanta[15,21] with energies of up to 85 mev, can be reconciled with the observed rise of the photofission cross section of Th^{232}, Bi^{209} and $Tl^{203,205}$ if the relative fission widths of these nuclei increase with increasing photon energy in the same way. From this, one can make the deduction that the rise in the photofission cross section of U^{238}, Th^{232}, Bi^{209} and $Tl^{203,205}$, observed for γ–quanta energies greater than 80 mev, depends on the rise of the absorption cross section for photons in nuclei. This is verified by other experimental data.[1,3]

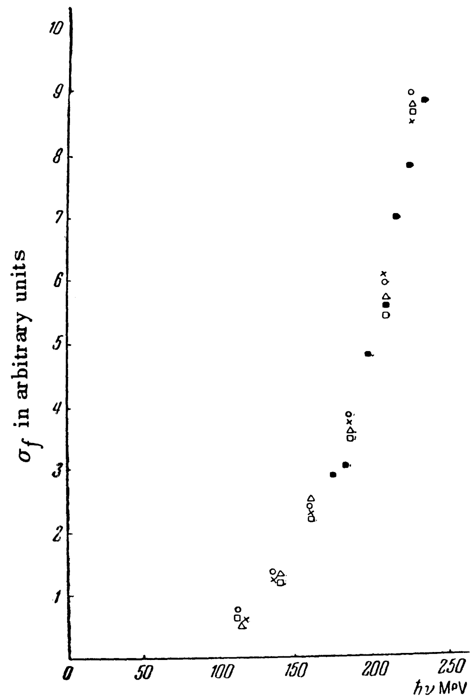

FIG. 8. Dependence of the photofission cross sections of U, Th, Bi and Tl, and of the total $\sigma(\pi^0) + \sigma(\pi^+)$ production cross section of mesons, on the photon energy. The magnitudes of the cross sections were normalized to 10 for $h\nu = 250$ mev. ×– U^{238} O–Th^{232}, Δ–Bi^{209}, □–$Tl^{203,205}$, ■–$\sigma(\pi^0) + \sigma(\pi^+)$.

An attempt was made[10] to estimate the photofission cross section of the Bi^{209} nucleus under the assumption that the rise in the photofission cross section above 150 mev is connected with the reabsorption of the mesons. Agreement with the experimental values σ_f was attained with $\Gamma_f/\Sigma\Gamma = 0.25$. However, experiments on the fission of Bi^{209} by slow π^--mesons[18] have given $\Gamma_f/\Sigma\Gamma$ a value one order of magnitude smaller which is confirmed by the results of this work. Therefore the rise observed above 150 mev and the magnitude of the photofission cross section cannot be explained only in terms of meson reabsorption. However, the similarity of the energy dependence of the photofission cross section and the photoproduction of mesons lead us to think that the very same interaction mechanism for γ-quanta with nuclei is responsible for the photoproduction of mesons and for the rise of the photofission cross section.

In conclusion we use this occasion to express our sincere acknowledgement to Professor P. A. Cerenkov for his constant attention to this work, to N.N.Novikov for help with carrying out the measurements, and also to I. V. Chuvilo for help in setting up the experiment and to Professor V. I. Goldanskii for discussion of the experimental results.

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Translated by Fay Ajzenberg-Selove
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Other Errata

Page	Column	Line	Reads	Should Read
Volume 4				
38	1	Eq. (3)	$\ldots \frac{\pi r^2 \rho^2 \rho^2_n}{\rho_s^2}$,	$\ldots \frac{\pi r^2 \rho^2 \rho_n}{\rho_s^2}$,
196		Date of submittal	May 7, 1956	May 7, 1955
377	1	Caption for Fig. 1	$\delta_{35} = \eta - 21 \cdot \eta^5$	$\delta_{35} = -21°\eta^5$.
377	2	Caption for Fig. 2	$\alpha_3 = 6.3° \eta$	$\alpha_3 = -6.3° \eta$
516	1	Eq. (29)	$s^2/c^2 \ldots$	s/c
516	2	Eqs. (31) and (32)	Replace $A_1 s^2/c^2$ by A_1	
497		Date of submittal	July 26, 1956	July 26, 1955
900	1	Eq. (7)	$\ldots \frac{i}{4\pi} \sum_{c,\alpha} \frac{\partial w_a(t, P)}{\partial P^\alpha} \ldots$	$\ldots 2\pi^2 i \sum_{c,\alpha} \ldots$
			(This causes a corresponding change in the numerical coefficients in the expressions that result from the calculation of the effects of the plasma particles on each other).	
804	2	Eq. (1)	$\ldots \exp\{-(\overline{T} - V')\}$	$\ldots \exp\{-(\overline{T} - V')\tau^{-1}\}$
Volume 5				
59	1	Eq. (6)	$v_l (1 \partial F_0/\partial x) + \ldots$ where E_l is the projection of the electric field E on the direction 1	$\overline{(v \partial F_0/\partial x)} + \ldots$ where the bar indicates averaging over the angle θ and E_l is the projection of the electric field E along the direction 1
91	2	Eq. (26)	$\Lambda = 0.84\,(1+22/A)$	$\Lambda = 0.84/(1+22/A)$
253		First line of summary	$Tl^{204, 206}$	$Tl^{203, 205}$
318	1	Figure caption	$\ldots e^2 mc^2 = 2.8 \cdot 10^{-23}$ cm,	$\ldots e^2/mc^2 = 2.8 \cdot 10^{-13}$ cm,
398		Figure caption	... to a cubic relation. A series of points etc.	... to a cubic relation, and in the region 10 – 20°K to a quadratic relation. A series of points ●, coinciding with points O, have been omitted in the region above 10°K.