Yields of Photoneutrons from Intermediate and Heavy Nuclei

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The yields of photoneutrons were measured for various maximum γ-bremsstrahlung energies lying between the threshold of the (γ, n) reactions up to $E_{max} = 27$ mev. The photoneutron cross section was determined by the "photon difference method" as a function of the photon energy from the yield curves for ten elements (copper, zinc, cadmium, iodine, tantalum, gold, thallium, bismuth, thorium and uranium).

IN the irradiation of nuclei with atomic number $Z \gtrsim 50$ by γ-quanta with energies 10-30 mev, reactions with emission of neutrons [(γ, n), $(\gamma, 2n)$, $(\gamma, 3n)$, . . .] are practically the only reactions associated with photodisintegration of the nuclei. The yield of protons relative to neutrons for nuclei with $Z \approx 50$ does not exceed 3-4%[1] and falls to a fraction of one percent for lead and bismuth[2]. The probability of the reaction (γ, γ') ought not to exceed several percent of the probability of emission of photoneutrons[3]. Thus the total cross section of these photoneutron reactions, with accuracy to within several percent, is equal to the cross section of absorption of γ-quanta, σ_γ, and the radiation yield of photoneutrons gives a series which is characteristic of the nuclear interaction of γ-quanta of the given energy.

In the present work, the yields of photoneutrons were measured for different maximum energies of γ-bremsstrahlung from the threshold of the reaction $(\gamma, n) = E_n$, up to $E_{max} = 27$ mev for the following ten elements: Cu, Zn, Cd, I, Ta, Au, Tl, Bi, Th and U.

MEASUREMENT OF THE YIELD OF PHOTONEUTRONS AND THE NEUTRON CROSS SECTION

The measurements were carried out on the synchrotron of the Physical Institute of the Academy of Sciences at 20 mev, which gives 150 γ-pulses per sec, each of about 20 μsec duration.

The irradiated samples were placed in the center of a paraffin block and delayed photoneutrons were recorded in the time intervals between the γ-pulses by an ionization chamber filled with BF_3. The absolute yield of the neutrons was calibrated by a standard source (Ra_α + Be). For all maximum energies, a correction was introduced for the different spatial distribution of neutrons in the paraffin and the absorption of γ-rays in the samples.

The number of photons incident per unit time on the irradiated specimen was measured by the ionization in the air space of a thickwalled aluminum dosimeter chamber (the thickness of the front wall was 7.5 cm)[4]. The method of measurement has been suitably described in the literature[5].

The yield curves of photoneutrons have been plotted in Fig. 1. The maximum energy of the γ-bremsstrahlung, E_{max}, is plotted along the abscissa; the ordinate gives the number of neutrons emitted per gram-molecule of sample per sec, for a flux of γ-radiation that gives rise to a current equal to 1 μA in the air space of the dosimeter chamber. Each experimental point on the yield curves represents the mean of five individual series of measurements. The mean square errors are shown (the statistical accuracy was appreciably higher).

The measured integral curves of the neutron yields permitted us to calculate the photoneutron cross section σ_n for different energies of the γ-quanta. The curves of the differential cross sections $\sigma_n(E)$ computed by the "photon difference method"[6], are plotted in Fig. 2. A Schiff spectrum was obtained for the γ-bremsstrahlung[7]. The curves have the typical shape of all photonuclear reactions--the resonance shape associated with the resonant character of the absorption of the γ-quanta by the nuclei.

The basic characteristics of the cross section curves are given in Table I: the cross section maximum $\sigma_{n\,max}$; the energy corresponding to the maximum cross section, $E_{\sigma_{n\,max}}$; the half width of the curve, and the integral cross section

$$\int_{E_n}^{E_0} \sigma_n \, dE \quad (E_0 = 27 \text{ mev}).$$

The cross section curves plotted in Fig. 2 were obtained from the continuous spectrum of γ-radiation as a result of a complicated calculation and

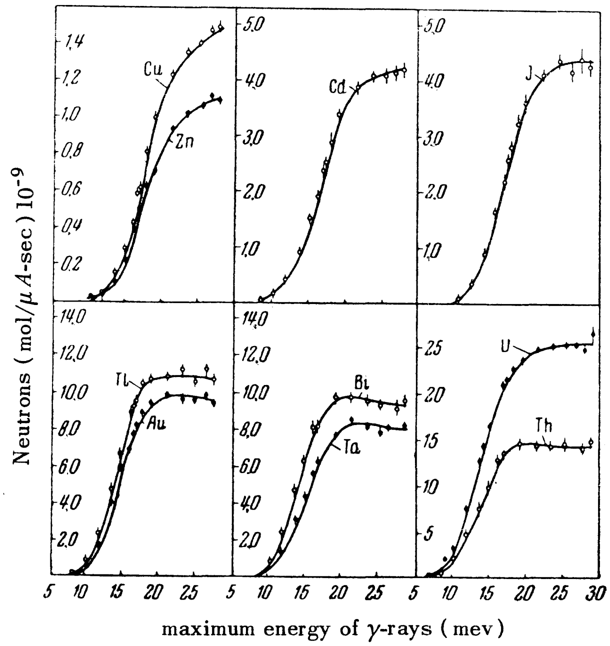

FIG. 1. Yield curves of photoneutrons.

TABLE I. Fundamental characteristics of photoneutron cross sections.

Element	$E_{\sigma_n \max}$ in mev	σ_n max in barns	Half width in mev	$\int_{E_n}^{E_0} \sigma_n (E)\, dE$ in mev-barns	$\int_{E_n}^{E_0} \sigma_n (E)\, dE / \sigma_n \max$
Copper	17.2	0.126	4.3	0.93	7.4
Zinc	16.3	0.082	6.3	0.66	8.1
Cadmium	16.0	0.270	6.4	2.28	8.4
Iodine	15.5	0.288	6.0	2.35	8.2
Tantalum	14.5	0.452	6.8	3.87	8.6
Gold	14.2	0.571	6 0	4 37	7.6
Thallium	14.6	0.655	5.4	4.99	7.6
Bismuth	13.9	0.537	5.9	3.96	7.4
Thorium	14.5	0.796	5.6	6.33	8.0
Uranium	14.9	1.18	6.8	12.5	10.6

the accuracy of these curves is much less than the accuracy of the measured curves of neutron yields (see Fig. 1). The position of the maximum of the curves is determined with accuracy ±5 mev. For the cross section maximum and the internal cross section, the errors amount to about 10%. With increase in energy, the error in the determination of the cross section increases, reaching 20-25% at the end of the curves.

The resultant integral cross sections for the photoneutron yields are given in Fig. 3 as a function of the atomic number of the nucleus. We have shown the corresponding maximum cross section $\sigma_{n\,\max}$ in this same graph. The integral cross section and the maximum cross section both increase with increase in Z ($\sim Z^{1.6}$). In the last column of Table I, the ratio

$$\int_{E_n}^{E_0} \sigma_n \, dE \,/\, \sigma_{n\ \max}.$$

is plotted.

For all the nuclei investigated, with the exception of uranium, for which the relative fission probability is about 0.3 [5], these ratios ranged from 7.4 to 8.5. One can then roughly consider that the integral cross section expressed in mev-barns is connected with the maximum cross section in barns by the following expression (up to 27 mev):

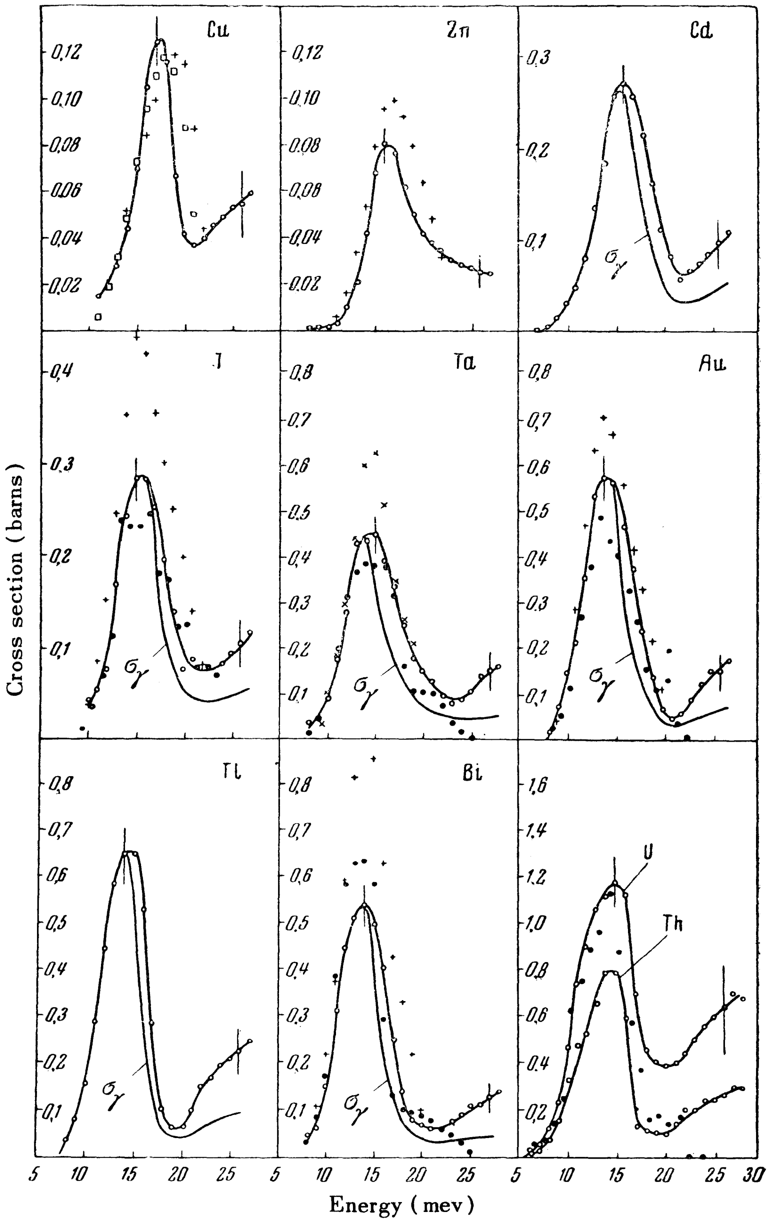

FIG. 2. Photoneutron cross section σ_n, computed from the yield curves by the "photon difference method". + -- cross sections obtained in Ref. 8, ● -- cross sections obtained in Ref. 9, × -- cross section measured in Ref. 10 for tantalum, □ -- cross section of the reaction (γ, n) for copper, obtained by summation of the cross sections of the (γ, n) reaction for Cu^{63} and Cu^{65} (with account taken of isotopic composition), measured in Ref. 6 by the radioactivity of the remaining nuclei. For Cd, I, Ta, Au, Tl and Bi, curves are presented for the cross sections of γ-quanta, computed from the statistical theory of nuclei.

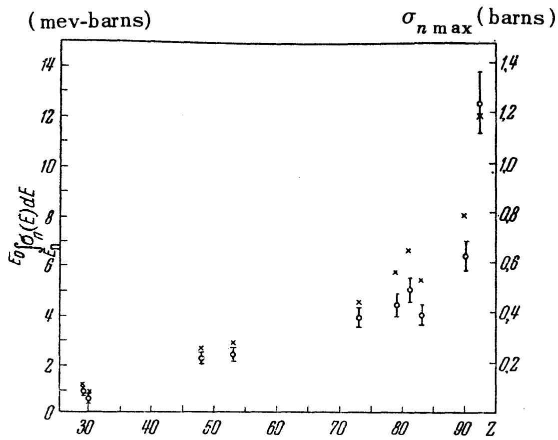

FIG. 3. Integral cross sections of photoneutron yield as functions of atomic numbers. Maximum values $\sigma_{n\,max}$ are shown by the crosses. The experimental points lie on the curve $Z^{1.6}$.

$$\int\limits_{E_n}^{E_0} \sigma_n \, dE \approx 8\sigma_{n\ \max}.$$

Similar results were obtained in the work of Montalbetti, Katz and Goldemberg[8], for 12 elements with $Z \geq 29$, and in the work of Nathans and Halpern[9] for 9 elements with $Z \geq 29$. In the first work the neutron yields were measured up to $E_{max} = 22$ mev, in the second, up to $E_{max} = 25$ mev.

The cross sections $\sigma_n(E)$ obtained by these authors for Cu, Zn, I, Ta, Au, Bi and U, are plotted in Fig. 2. For Cd, Tl and Th, the similar curves in the literature have not been shown. As is evident from the drawing, the cross sections obtained in Refs. 8 and 9 differ rather widely from one another. The curves obtained in the present work lie between them as a rule. In the region of energy above 20 mev, the path of the curves $\sigma_n(E)$ obtained in our research, diverges sharply from those obtained in Ref. 9 for Ta, Au, Bi and U. The decrease of the cross section, almost to zero, observed by Nathans and Halpern, is probably connected with inaccurate consideration of the final points which lie close to the sharp fall-off of the cross section curves. In our case the accuracy of the calculation of these points was controlled by the cross sections at the higher energies, which took on anomalously large values for a decrease in the cross section in the interval 20-30 mev. Different variants of calculations, carried out for the neutron cross section curves, gave appreciable values of the cross section σ_n in all cases (for

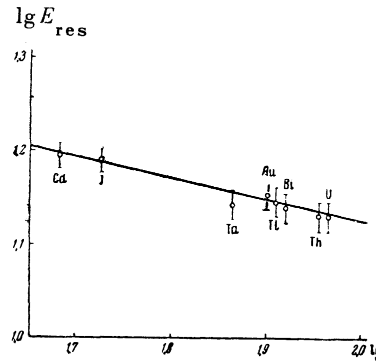

FIG. 4. Dependence of the resonance energy of the absorption of γ-quanta on the atomic number of nuclei. For uranium and thorium, E_{res} are obtained as the results of estimates given in Ref. 5.

energies of about 30 mev).

ABSORPTION CROSS SECTION OF γ-QUANTA

As was pointed out above, for nuclei with $Z \geq 50$, in energies of the excitation considered, the yield of photoprotons relative to the neutrons was very small. For such nuclei the measured photoneutron cross section was equal to

$$\sigma_n(E) \approx \sigma(\gamma, n) + 2\sigma(\gamma, 2n) + 3\sigma(\gamma, 3n) + \ldots \approx \sigma_\gamma(E)\,\bar{n}(E),$$

where $\bar{n}(E)$ is the mean number of neutrons emitted by the nuclei at the excitation energy E. In accord with statistical theory, we consider the relative probability of the reactions (γ, n), $(\gamma, 2n)$, . . . , and $\bar{n}(E)$ for different excitation energies, and can then obtain curves for the absorption cross section of the γ-quanta, $\sigma_\gamma(E)$.

The relative yields of the reaction $(\gamma, 2n)$, measured experimentally for several isotopes, agree well with the theoretical; therefore, the curves of $\sigma_\gamma(E)$ computed in this fashion ought to be close to the actual ones. Such a calculation was completed for Cd, I, Ta, Au, Tl and Bi. In the case of U and Th, neutrons are also emitted in the photofission of the nuclei; an estimate of $\bar{n}(E)$ was not obtained because of the absence of data on the ν-physical--the number of neutrons emitted immediately in the fission process for various energies of excitation.

In Table II we have plotted the thresholds of photoneutron reactions which are energetically possible, for energies of excitation of nuclei up to 27 mev for the nuclei under consideration. The

TABLE II. Threshold of photoneutron reactions (mev).

Element	(γ, n)	(γ, 2n)	(γ, 3n)	(γ, 4n)
Cadmium	6.7	14.6	23,0	>30
Iodine	9.4	16.2	26.0	32.9
Tantalum	7.6	13.9	21.6	28.2
Gold	8.1	14.9	23.9	⩾30
Thallium	7.5	14.0	22	28.8
Bismuth	7.4	14.2	22.5	29 6

binding energies of the neutrons were taken from the table prepared by Kravtsov[11]. For cadmium and thallium, $\bar{n}(E)$ were computed for each isotope separately and then averaged by means of the percent composition of each isotope. According to Weisskopf[12], the constant a in the expression for the density of levels of the remaining nucleus, $\omega = Ce^{\sqrt{aE}}$, was taken equal to $3.35\,(A-40)^{1/3}$. The resultant curves for $\sigma_\gamma(E)$ were plotted in Fig. 2, together with the curves of the cross sections $\sigma_n(E)$. In Table III we have listed the basic characteristics of these curves.

In accordance with the currently available theoretical considerations, for photon energies 10-30 mev, there appears to be a dipole mecahnism of absorption of γ-radiation by the nuclei[13-16]. In different theoretical works which treat this question, the following quantities were computed which characterize the cross section for absorption of the γ-quanta: the resonance energy E_{res}[14,15], the integral cross section

$$\int_0^\infty \sigma_\gamma\, dE$$

(see Ref. 16); the average energy

$$\bar{E} = \int E\sigma_\gamma\, dE \Big/ \int \sigma_\gamma\, dE$$

(see Ref. 16), and the moments

$$\int_0^\infty (\sigma_\gamma / E)\, dE$$

(see Ref. 17) and

$$\int_0^\infty (\sigma_\gamma / E^2)\, dE$$

(see Ref. 13). The dependence of the resonance energy E_{res} on the atomic number of the nucleus is plotted in Fig. 4. The logarithms of the corresponding quantities are plotted along the coordinate axes. Copper and zinc were excluded from consideration, since, because of the high probability of the reaction (γ, p), the position of the maximum of the cross section σ_n could not be identified with E_{res}. The straight line drawn through the experimental points gives the dependence $E_{res} = 35.9\,Z^{-0.215}$ or $E_{res} = 38.0\,A^{-0.188}$. Considering the large errors in the computation of the cross section curves, the resultant expressions agree very well with the expressions for $E_{\sigma_{n\,max}}$ obtained in Ref. 8: $E_{\sigma_{n\,max}} = 37\,A^{-0.186}$, and in Ref. 9: $E_{\sigma_{n\,max}} = 38.5\,A^{-0.186}$. The different models used in Refs. 14 and 15 give the dependencies $A^{-1/3}$ and $A^{-1/6}$.

According to Ref. 16, the integral cross section is

$$\int_0^\infty \sigma_\gamma\, dE = 0{,}06\,\frac{ZN}{A}(1+0{,}8\,x),$$

where x is the exchange part of the potential of the

TABLE III. Characteristics of the cross section of absorption of γ-quanta by nuclei.

Element	E_{res} in mev	$\sigma_\gamma(E=E_{res})$ in barns	half width in mev	$\int_{E_n}^{E_0}\sigma_\gamma\, dE$ in mev-barns	$\int_{E_n}^{E_0}\sigma_\gamma dE/0{,}06\times(ZN/A)$	$\int_{E_n}^{E_0}(\sigma_\gamma/E)\, dE$	$\int_{E_n}^{E_0}(\sigma_\gamma/E^2)dE$	$r_0\times10^3$ in cm
Cadmium	15.6	0,263	5,1	1,76	1,06	0,111	0,00745	1,26
Iodine	15,5	0,288	4,9	1,86	1,00	0,117	0,00768	1,16
Tantalum	13.9	0,448	4,5	2,74	1,05	0,190	0,0139	1,15
Gold	14.2	0,571	4,7	3,49	1,23	0,244	0,0182	1,23
Thallium	14.0	0,648	4,6	3,77	1,28	0,266	0,0200	1.25
Bismuth	13.8	0,537	4,8	3,12	1,04	0,230	0,0178	1,16

nuclear forces.

In Table III are plotted the integral cross sections obtained from the curves of

$$\sigma_\gamma, \quad \int_{E_n}^{E_0} \sigma_n \, dE$$

and the ratio

$$\int_{E_n}^{E_0} \sigma_\gamma \, dE \,/\, 0.06 \frac{ZN}{A}, \quad (E_0 = 27 \text{ mev}).$$

Inasmuch as the σ_γ are not large, even for energy $E = 27$ mev, the integral cross sections shown in Table III ought to be less than the integral cross sections computed theoretically. The average value of x, obtained from our data, and equal to 0.14, gives a lower limit for the magnitude of the exchange forces. Calculation of the cross section σ_γ for higher energies ought to give higher values for x.

In Refs. 8 and 9, in which the neutron yields were measured for $E_{max} = 22$ and 25 mev, respectively, the authors computed x, improperly setting

$$\int_{E_n}^{E_{max}} \sigma_n \, dE = \int_0^\infty \sigma_\gamma \, dE.$$

The value of $x = 0.4$-0.5 obtained by them for heavy nuclei can be shown to be correct only because of the accidental compensation of the higher cross section by the lower upper limit of integration.

The values of the average energies that we obtained were not computed, since the cross sections for energies higher than 27 mev ought to make a relatively large contribution in this case.

The error due to the finite upper limit of the integration is less for the integral $\int \frac{\sigma_\gamma}{E} dE$. According to the calculations of Khokhlov[17],

$$\int_0^\infty \frac{\sigma_\gamma}{E} dE = 4\pi^2 \frac{e^2}{\hbar c} r_0^2 A^{2/3} \left[\left(\frac{N}{A} \right)^2 \varphi(Z) + \left(\frac{Z}{A} \right)^2 \varphi(N) \right].$$

The function $\varphi(n)$ used in the paper was computed for finite and infinite depth of the potential well. Assuming the experimental values of

$$\int_{E_n}^{E_0} \frac{\sigma_\gamma}{E} dE = \int_0^\infty \frac{\sigma_\gamma}{E} dE,$$

one can compute the value of the universal radius r_0. The mean value of r_0, obtained in this fashion, is equal to 1.0×10^{-3} cm for the finite well and 1.2×10^{-13} cm for the infinite well.

The small value of r_0 obtained for the finite well, which is the more realistic case, substantiates the idea that the cross sections σ_γ have a significant value for energies greater than 30 mev.

The smallest effect for neglect of energies higher than 27 mev ought to be that for $\int \frac{\sigma_\gamma}{E^2} dE$. It follows from the work of Migdal[13] that

$$\int_0^\infty \sigma_\gamma \frac{dE}{E^2} = \frac{\pi^2}{20\beta} \frac{e^2}{\hbar c} A R^2 = \frac{\pi^2}{20\beta} \frac{e^2}{\hbar c} r_0^2 A^{5/3},$$

where β is a coefficient characterizing the "affinity" of neutrons and protons in the Weisskopf formula and is approximately 20 mev. The values of r_0 obtained from this formula, if we set the experimental

$$\int_{E_n}^{E_0} \sigma_\gamma \frac{dE}{E^2}$$

equal to

$$\int_0^\infty \sigma_\gamma \frac{dE}{E^2},$$

are given in the last column of the Table. For all six nuclei, r_0 is equal to 1.2×10^{-13} cm, which is in excellent agreement with the value given in recent researches.

This comparison shows qualitative agreement of the experimental results with the data of theoretical calculations obtained under the assumption of a dipole absorption mechanism for the γ-rays. Quantitative comparison with the theoretical expressions, with the exception of the final integral, requires the measurement of the neutron yield at high energies. It is appropriate to carry out such researches in monochromatic measurements.

In conclusion, we take this opportunity to express our gratitude to Iu. K. Khokhlov for fruitful discussions.

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