[5] R. Wolfgang and G. Friedlander, Phys. Rev. 96, 190 (1954)

[6] J. Sharpe and G. Stafford, Proc. Phys. Soc. (London) A 64, 211 (1951)

[7] A. Cameron, Phys. Rev. 82, 270 (1951)

Translated by I. B. Berlam
109

Maximum Yield of Photoneutrons and a New Method of Determining the Integral Cross-Section of (γ, n) Reactions for High Energy Photons

V. I. GOL'DANSKII AND V. A. SHKODA-UL'IANOV
P. N. Lebedev Physical Institute

(Submitted to JETP editor January 25, 1955)
J. Exper. Theoret. Phys. USSR 28, 623-626 (May, 1955)

DURING the past year, thanks to the use of the new methods of electron acceleration -- the betatron and the synchrotron -- a wide range of photonuclear reactions, originating under the action of hard bremsstrahlung, was investigated. It was soon established that for a series of photonuclear reactions, the dependence of the cross section on the photon energy was characterized by the presence of a maximum at the energies in the range 10-25 Mev. The cross section decreased rapidly on both sides of this maximum.

The characteristic resonance character of the excitation function of photonuclear reactions is connected with the excitation in the resonance region of the nuclear dipole oscillations, the theory of which was first given by Migdal[1]. Among the widely investigated photonuclear reactions posessing dipole resonances were reactions producing photoneutrons. In the experiment the following characteristics of the photonuclear reactions were determined: the threshold energy of γ-quanta, E_p, the resonance energy, E_r, as determined by the maximum in the cross section, the half-width of the resonance peak, ΔE, the maximum cross section for the reaction, σ_r, and the integral cross section $\int \sigma(E)\,dE = \sigma_{int}$. All of these characteristics were determined for independent reactions of the type, (γ, n), (γ, pn), $(\gamma, 2n)$. In most of the work these reactions were identified by radioactive isotopes that were produced. By far the smaller amount of work was that in which a neutron detector detected all the neutrons having been emitted by the elements under investigation (for papers or reported work on the production of photoneutrons see references 2, 3). Thus, the yield of photoneutrons in an independent (γ, n) reaction was shown to be similar to the total yield of photoneutrons for the given isotope. From this fact it is possible to conclude that the basic source for the production of photoneutrons, even at high maximum energy of the bremsstrahlung (320 Mev), is the simple (γ, n) reaction.

As a rule, in photonuclear investigations, thin samples have been used as photoneutron sources in which there has been no electro-photon multiplication of the emitted γ-quanta. In our work another goal was set -- the determination of the yield of photoneutrons under the conditions of total development of the electron-photon shower, i.e., the determination of the maximum coefficient for converting photons into neutrons. Thus, the measurements gave, simultaneously, the possibility of determining the integral cross section of the reaction producing the photoneutrons, as well as the possibility of using the equilibrium condition from shower theory[4], i.e., integrating according to the depth of the shower neutron spectrum, produced by the primary γ-quanta with dimensionless energy, ϵ_0 (where $\epsilon_0 = 2.29\, E/\beta$, and β is the critical energy for the given substance):

$$\Gamma_\Gamma(\varepsilon_0, \varepsilon) = (1/\beta\mu(\varepsilon))\,[\chi(\varepsilon_0, \varepsilon)\,\varepsilon_0/\varepsilon + 2{,}29\delta(\varepsilon_0 - \varepsilon)].$$

Here

$$\chi(\varepsilon_0, \varepsilon) = \varepsilon e^{\varepsilon} \int_{\varepsilon}^{\varepsilon_0} e^{-x} \frac{dx}{x^2} - \frac{\varepsilon}{\varepsilon_0^2}[1 - e^{-(\varepsilon_0 - \varepsilon)}],$$

and the dimensionless cross-section for the absorption of the neutrons is

$$\mu(\varepsilon) = \sigma(E)\,Nt,$$

where N is the density of the substance (in number of nuclei per cm^3), and t is the unit shower length (in cm).

It is obvious that the maximum yield of photoneutrons from an infinite mass of the substance is

$$Q_{\max} = \int_{E_1}^{E_2} \frac{\sigma_{\gamma n}(E)\,dE}{Nt} \int_{\varepsilon_1}^{\varepsilon_m} \Gamma_\Gamma \frac{a\,d\varepsilon_0}{\varepsilon_0},$$

where E_1 and E_2 are the lower and the upper limits of the resonance region, $\sigma_{\gamma n}$ is the photonuclear cross section of the reaction for the formation of photoneutrons, and the emitted spectrum of the bremsstrahlung takes the form $f(\epsilon) = a/\epsilon$ (we note, that for a calculation on the equilibrium spectrum this approximation gives a smaller error than for a direct determination of the cross section in a calculation of this form).

The first integration produces the result

$$Q_{\max} = a \int_{E_1}^{E_2} \frac{\sigma_{\gamma n}(E)\,dE}{\sigma_{\text{absorp}}(E)\,E} \left[1 + \frac{I(\varepsilon)}{2.29}\right],$$

where

$$I(\varepsilon) = \varepsilon_m + \frac{\varepsilon}{\varepsilon_m} - \varepsilon\left(1 + \frac{1}{\varepsilon_m}\right)\exp\left[-(\varepsilon_m - \varepsilon)\right]$$

$$+ \varepsilon e^{\varepsilon}(\varepsilon_m + 2)\left[\mathrm{Ei}(-\varepsilon) - \mathrm{Ei}(-\varepsilon_m)\right].$$

In computing the narrow resonance region, we took out of the integral, the denominator $\overline{\sigma}_{absorp}(E)E_p$, and the multiplier $1 + [I(\epsilon_p)/2.29]$. This is valid for the case when $\epsilon_p \ll \epsilon_m$:

$$I(\varepsilon_p) \approx \varepsilon_m + \varepsilon_p e^{\varepsilon_p}(\varepsilon_m + 2)\,\mathrm{Ei}(-\varepsilon_p).$$

Then

$$Q_{max} \approx \frac{a}{\overline{\sigma}_{absorp}E_p}\left[1 + \frac{I(\varepsilon_p)}{2{,}29}\right]\int_{E_1}^{E_2} \sigma_{\gamma n}(E)\,dE$$

$$= \frac{a\sigma_{int}}{E_p\overline{\sigma}_{absorp}}\left[1 + \frac{I(\varepsilon_p)}{2.29}\right].$$

Experiments for determining the maximum yield of photoneutrons and the integral (γ, n) cross section were performed in June and July of 1951. A beam of bremsstrahlung photons with a maximum energy of 250 Mev passed through a port 10.5 × 10.5 cm into a paraffin block with dimensions of 70 × 70 × 70 cm. In the center of the block were placed photoneutron sources -- cubes of Fe and Cu with dimensions 10 × 10 × 10 cm and samples of Pb and U, 10 × 10 cm^2 in area and of various thicknesses. The flux of γ-rays was determined by means of an integrating chamber. All of the data was obtained with a standard flux equal to $a = 6.5 \times 10^9$ sec^{-1}. The yield of photoneutrons was detected by means of an indium detector, wrapped in cadmium. Neutrons near the resonance of the reaction $In^{115}(n,\gamma)In^{116}$ with an energy of ~ 1.44 ev were detected. The calibration of the yield of neutrons was made by comparing the area under the slowing-down curve with the result from a standard Ra-Be source ($Q = 1.2 \times 10^7$ sec^{-1}) which was placed under the same conditions.

Investigations on the slowing-down curve also permitted the determination of the increase of the photoneutrons moderated to the energy of the indium resonance. This increase was compared to the increase of the moderated Ra-Be neutrons to this same energy. These determinations were made under the following conditions: there was a through port in the paraffin block and there was a lead lining around the Ra-Be source (so that the dimensions and the materials of the neutrons' sources were identical). Knowing the increase of the neutrons, we were able to calculate also the average energy of the photoneutrons, $\overline{E}_n$. Aside from the basic work, measurements of the background were made by means of the activity induced in indium when the blocks -- the source of the photoneutrons -- were removed. Up to a distance of 30-40 cm from the axis of the beam, the background was about 5% of the activity produced by the photoneutrons from lead for $(Q_n)_{max}$ and did not exceed 20% (of the experiments with Fe). We approximate the precision for determining Q_n as

Neutron Source	Q_n sec^{-1}	τ_n (cm^2)	E_r mev	$\overline{\sigma}_{abs}$ (bn)	σ_{int} (mev-bn)	$\overline{E}_n$ (Mev)
Ra - Be	1.2×10^7	~ 64				~ 4
Fe	2.4×10^8	~ 40	18.4	3.0	(1.3)	~ 2.1
Cu	4.4×10^8	~ 40	18	3.5	(2.1)	~ 2.1
Pb (1 cm)	2.10^8	~ 35	12.2	18.3		~ 1.9
Pb (2 cm)	3.3×10^8					
Pb (6 cm)	7.3×10^8					
Pb (8 cm)	8.7×10^8					
Pb (10 cm)	10^9					
Pb (19 cm)	$10^9 = Q_{max}$				5.2	
U* (2 cm)	7.3×10^8	~ 30	11.3	21.4		~ 1.7
U (4 cm)	1.1×10^9					
U (8 cm)	1.5×10^9					
U (12 cm)	$1.6 \times 10^9 = Q_{max}$				8.2	

* The yield of neutrons from U is corrected for secondary fission photoneutrons.

$\pm 10\%$ (for Pb and U) and $\pm 20\%$ (for Fe and Cu). The accuracy of determining the integral cross section also depends on the accuracy of the determination of the absolute intensity of the neutron beam, being approximated as $\pm 10\%$. For checking this, the yield of neutrons from pure carbon was compared to that from carbon in paraffin. This was done to determine if scattered-unwanted-neutrons would be detected as well as the photoneutrons. The yields were shown to be identical within the limits of error of the measurements, demonstrating the absence of scattered-unwanted-neutrons. In the Table are shown the results of the experiments.

According to the maximum yield of photoneutrons from lead and uranium the determination of the integral cross section for these elements agreed with other data in the literature[2,3].

This agreement is evident from the applicability of the proposed method for determining the integral cross section. The assumption that for uranium $(\sigma_{\gamma n})_{\rm int} = 92/82\,(\sigma_{\gamma n_{\rm Pb}})_{\rm int}$, gives for the photofission of uranium for $\nu_n = 2.5$ the value $(\sigma_{\rm fiss})_{\rm int} = (8.2 - 5.8)/2.5 \approx 1$ Mev-bn. The maximum coefficient for converting into photoneutrons of the photons from bremsstrahlung with energies from the threshold of the (γ, n) reaction for lead (6 Mev) to 250 Mev is equal to

$$\alpha_{\gamma n} = Q_{\text{макс}} \Big/ \int\limits_{E_1}^{250\text{MeV}} \frac{a}{E}\, dE \approx 0{,}04.$$

For Fe and Cu the maximum yield of photoneutrons was not determined, because the geometrical conditions of our experiment required the approximation of a point source, and since the dimensions of the blocks were $10 \times 10 \times 10$ cm, only in the case of the heavy nuclei was the electron-photon shower completely developed, and the limiting value of the yield of the neutrons reached. Approximate appraisal of the maximum yield of photoneutrons from Fe and Cu can be made, since certain energy resonances of the (γ, n) reaction, as for Pb and U, do not lie below the critical energy, by assuming that the ratio $Q_n/Q_{\max}$ is identically dependent for all the enumerated elements on the thickness of the block in t-units. Such an approximation gives an integral cross section of 1.3 Mev-bn for iron and 2.1 Mev-bn for copper.

Likewise, measurements of the yield of photoneutrons were made for the light nuclei (C, Al). However, in the cubes of 10 cm thickness in the case of these substances, the electron-photon shower was even less developed. Therefore, there is required the use of the more complicated computation of the shower theory, whose description goes beyond the limits of the present communication.

The method of determining the integral (γ, n)-cross section and the maximum yield of photoneutrons by means of a simple calculation for an equilibrium shower spectrum can certainly be useful, also for the light nuclei. In this case it is necessary to use a block of larger dimensions, determining the number of photoneutrons not by means of a slowing down curve, but by a direct method, i.e., by detecting the photoneutrons being emitted at the various angles by means of a flat boron counter or a fission chamber of U^{235}.

In conclusion, the determination of the maximum yield of photoneutrons by means of developing showers from photons of high energy shows an interesting possibility for calculating the conversion of the electron-photon components of cosmic rays into nucleons.

1 A. B. Migdal, J. Exper. Theoret. Phys. USSR **15**, 81 (1945)

2 *Problems of Modern Physics* 8, *Photons of large energy and photonuclear reactions*, 1952

3 *Photonuclear Reactions*, Collection of articles, Moscow, 1953

4 C. Z. Belen'kii, *The Shower Process in Cosmic Radiation*, State Publishing House, Moscow, 1948

Translated by I. B. Berlam
110

The Fission of Uranium Nuclei Under the Action of Slow Π^- Mesons and High Energy Particles

G. E. BELOVITSKII, T. A. ROMANOVA, L. V. SUKHOV AND I. M. FRANK

P. N. Lebedev Institute of Physics, Academy of Sciences, USSR

(Submitted to JETP editor March 9, 1955)

J. Exper. Theoret. Phys. USSR **28**, 729-732 (June, 1955)

IN this work, investigation was made of the fission of uranium nuclei by slow π^- mesons[1,2] * by fast neutrons up to 460 mev, and by γ rays up to 250 mev[6]. For the recording of the fission of uranium nuclei, photographic plates were used with an emulsion of 100 μ thick, into which there was