(γ, p) REACTION ON Au^{197}

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Energy and angular distributions of protons from irradiation of gold with bremsstrahlung having $E_{\gamma max} = 22.5$ Mev were obtained. The results are compared with calculations based on the statistical theory and on the theory of a direct photoeffect.

PROTON yields from irradiation of heavy elements ($Z > 70$) with bremsstrahlung having $E_{\gamma max} \sim 23$ Mev are 2 or 3 orders of magnitude greater than the yields predicted by the statistical theory of nuclear reactions.[1] The spectra of the photoprotons also contradict this theory. Energy distributions computed from Courant's theory of a direct photoeffect for nuclei like Bi^{209}, Ta^{181}, and Pb^{208} have a shape which is in good agreement with the experimental data of Toms and Stephens.[2] However the yields are 3.3 — 13 times less than the measured yields.

The published data of Dawson[3] on the energy distribution of photoprotons from gold do not agree with either the statistical theory or the direct photoeffect proposed by Courant. His distributions could not be badly distorted by the contribution of deuterons. According to an estimate made in reference 4, this contribution amounted to about 12%. However, the maximum energy of the photon spectrum in reference 3 was set way above the region of the giant resonance — it was equal to 70 Mev. Protons with energies up to 17 Mev were recorded. This could lead to a sizeable contribution of more complex photodisintegrations with emission of protons and, consequently, would make more difficult the analysis of the experimental results.

In the present work, we have measured the energy and angular distribution of photoprotons from irradiation of gold with bremsstrahlung having $E_{\gamma max} = 22.5$ Mev. The results are compared with the statistical theory and with Courant's theory of a direct photoeffect, and also with computations using a theory of direct resonance emission of nucleons, which takes into account the shell structure of the nucleus.[5]

EXPERIMENTAL ARRANGEMENT

The apparatus and the experimental setup have been described in reference 4. The source of γ radiation was the synchrotron of the Physico-technical Institute. A 58 mg/cm^2 gold foil, placed at an angle of 30° to the gamma beam, was irradiated. An area of 1.7×1.5 cm^2 was subjected to the γ radiation. NIKFI-Ya2 nuclear emulsions, with a thickness of 200 μ, recorded the protons at angles of 20, 40, 50, 60, 70, 80, 90, 100, 110, 120, 140, and 160° with respect to the axis of the beam. The mean angle of entry of particles into the emulsions was 8°. The distance from the center of each photoplate to the center of the target was 8.5 cm. The multiplate chamber was shielded with a 10 cm layer of paraffin and a layer of lead of the same thickness.

For the measurements on the photoplates, we selected particle tracks longer than 60 μ, which started from the emulsion surface and were at angles which satisfied the geometrical conditions of the experiment. It was not possible to distinguish singly-charged particles in the emulsion. However the yield of photodeuterons from Au^{197} is an order of magnitude less than the yield of photoprotons. The yield of tritons is still smaller. Because of this, all the selected tracks could be assumed to be proton tracks. The proton energies were determined from their measured range in emulsion and the known range-energy curve. Corrections were made for energy loss in the effective half-thickness of the target.

Deuterons with a range > 60 μ, coming from (γ, d) reactions and recorded as protons, gave a background amounting to $\sim$ 12%.[4] In addition, the interaction of the scattered radiation with the chamber wall material produced a background of protons. These were mainly protons with energies < 4.5 Mev. In the energy range of 7 — 17 Mev, they amounted to about 3%. The background from α particles of acceptable range was < 1%.

RESULTS AND DISCUSSION

The complete energy distribution of the photoprotons over the range 7 — 17 Mev is shown in the histogram of Fig. 1.

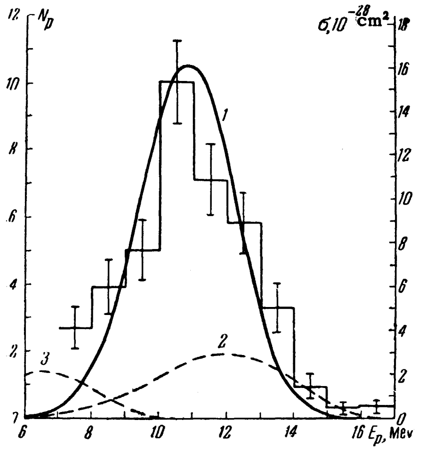

FIG. 1. Proton energy distribution. 1 – energy spectrum from the theory of direct resonance emission of nucleons; 2 – energy spectrum from Courant's theory of a direct photoeffect; 3 – energy spectrum from statistical theory.

The failure of the evaporation model to explain the energy distributions and yields of photoprotons from heavy elements led to the assumption that in this case the (γ, p) reaction goes mainly via a direct photoeffect. In Fig. 1, the solid curve shows the energy distribution of photoprotons computed from the theory of direct resonance emission of nucleons, according to the paper of Wilkinson.[5] In computing this curve we used the scheme of single-particle levels suggested by Klinkenberg.[6] The nuclear radius was taken equal to $1.3 \times 10^{-13} A^{1/3}$ cm.

The penetrabilities of the barriers for protons of various angular momenta and energies were computed by the WKB method. The depth V of the potential well was treated as a parameter. To get agreement between computed and experimental spectra required a value of V equal to ~ 53 Mev. Small changes of well depth had little effect on the location of the maximum, which was at 10.9 Mev. The table lists the proton transitions

Proton transitions	Proton yield, %
$2d_{3/2} \rightarrow 2f_{5/2}$	0.9
$2d_{3/2} \rightarrow 3p_{1/2}$	56.9
$2d_{3/2} \rightarrow 3p_{3/2}$	4.9
$2d_{5/2} \rightarrow 2f_{5/2}$	0.1
$2d_{5/2} \rightarrow 3p_{3/2}$	37.1
$1g_{7/2} \rightarrow 2f_{5/2}$	0.1
	100

in Au^{197} which give significant contributions to the emission of direct resonance photoprotons. The column on the right gives the relative yields of direct resonance photoprotons from these transitions. We see that most of the protons from direct resonance photoemission come from d → p transitions. Curve 1 is normalized so that the area under it in the energy interval 10.2 – 17 Mev is equal to the area under the experimental histogram over the same energy interval. Such a normalization assumes that all protons with energy > 10.2 Mev are due to the direct resonance photoprocess. As we see from the figure, the shape of the theoretical spectrum is quite close to the experimental shape.

The ratios computed by Wilkinson of the cross sections for emission of direct resonance protons to the total cross sections for absorption of bremsstrahlung with $E_{\gamma\,max}$ = 23 Mev in heavy nuclei are in good agreement with experiment.[5] For gold this ratio was equal to approximately 0.14%. If we use the data of reference 7, in which they found essentially the total integral cross section for absorption of γ quanta with this same maximum energy, the integral cross section for the (γ, p) reaction on Au^{197} will be equal to ~ 6.1×10^{-27} Mev-cm^2. In accordance with this number, we have added an absolute scale of ordinates at the right of Fig. 1.

The dashed curve 2 shows the spectra of protons from the direct photoeffect, obtained using Courant's theory.[8] The shape of the energy distribution was computed from the formula[2,3]

$$I(\varepsilon) \approx f(\varepsilon) \int_{B_p+\varepsilon}^{E_{max}} N_\gamma(E)\, E^{-3} dE,$$

where $I(\epsilon)$ is the relative number of protons with energy ϵ; $f(\epsilon)$ is the penetrability of the potential barrier;[9] B_p = 5.72 Mev is the binding energy of the proton in Au^{197};[1] E_{max} is the maximum energy of the bremsstrahlung; $N_\gamma(E)$ is the number of photons of energy E in the spectrum.

Using the formulas given in reference 8, we computed the absolute cross section for emission of protons with an arbitrarily chosen energy (11.3 Mev). The depth of the potential well and the order of filling of the single-particle levels by protons was assumed to be the same as in the computation using Wilkinson's theory. From the shape of the spectrum and the value at this reference point, the energy distribution was drawn on an absolute scale. The maximum of the spectrum was found to be close to the experimental value. However the area under the curve gives an integral cross section of 1.15×10^{-27} Mev-cm^2, i.e., approximately five times smaller than Wilkinson's theory.

As a result of collisions with other nucleons in the nucleus, protons which have absorbed a γ quantum are lost to the direct photoprocess. This loss from the direct photoprocess can be taken into account approximately by introducing into Courant's formula for the total cross section an "escape" coefficient equal to $3\lambda/4R$. Here λ is the mean free path of nucleons in nuclear matter and R is the nuclear radius. For proton energies corresponding to our experiment, λ is $\sim 3.5 \times 10^{-13}$ cm.[10] For Au^{197}, the coefficient is 0.35. If we take account of this probability of "escape" of protons from the nucleus without collision with other nucleons, the integral cross section from Courant's theory becomes 15 times less than that predicted by the theory of direct resonance emission of nucleons.

It should be mentioned that the experimental yields of protons from the (γ, p) reaction ($E_{\gamma max} = 23$ Mev) on Bi^{209}, Ta^{181}, and Pb^{208} are, respectively 3.3, 8, and 13 times greater than the yields computed from Courant's theory.[2]

The dashed curve 3 shows the proton energy distribution computed according to statistical theory, using the formula[3]

$$I(\varepsilon) = \varepsilon\sigma_c(\varepsilon)\, e^{-\varepsilon/T} \int\limits_{B_p+\varepsilon}^{E_{max}} N_\gamma(E)\, \sigma_{\gamma,n}(E)\, dE,$$

where $\sigma_c(\epsilon)$ is the cross section for capture of a proton with energy ϵ by the residual nucleus;[9] $\sigma_{\gamma,n}(E)$ is the cross section for the (γ, n) reaction on gold for quantum energy E;[7] T is the temperature of the residual nucleus in Mev.

The curve was normalized so that the area under it in the range 7 — 17 Mev was equal to the difference between the area under the experimental curve and the area under the curve corresponding to Wilkinson's theory. The best agreement with the experimental spectrum was obtained for T = 0.54 Mev. Such a value of T does not contradict existing data on nuclear temperatures for heavy elements. The maximum of the distribution was around 6.5 Mev. Curve 3 shows that the possible contribution from protons caused by an evaporation process is small. It can amount to several percent of the total yield of the (γ, p) reaction. In view of the overlap of the energy regions of protons from the direct photoeffect and from evaporation, it does not appear possible to give a more exact value for this contribution.

According to the theory of the direct photoeffect,[5,8] the angular distribution from transitions of the type $l \to l-1$ has the form

$$d\sigma_{l \to l-1} \sim 1 + \frac{1}{2}\frac{l-1}{l+1}\sin^2\theta,$$

where l is the initial orbital angular momentum of the proton. Computation of the energy spectrum according to the theory of direct resonance emission of nucleons showed that 99% of the protons in direct photoemission are caused by $d \to p$ transitions. For such transitions,

$$d\sigma_{2\to 1} \sim 1 + 0.17\sin^2\theta.$$

In other words, an almost isotropic distribution is predicted. In Fig. 2 we show the angular distribution for 197 protons with energies 9 — 15 Mev.

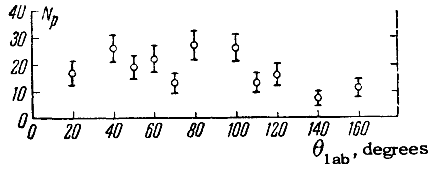

FIG. 2. Proton angular distribution.

The maximum error in determination of solid angles is < 15%. Only the statistical errors are shown on the graph. The observed angular distribution is close to isotropic, and is not in contradiction with expected shape for $d \to p$ transitions.

It is interesting to note that the angular distribution of protons with energies 8 — 11 Mev, obtained by Dawson,[3] was also almost isotropic.

The computations show that the theory of direct resonance emission of nucleons agrees best with our experiment.

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Note added in proof (December 15, 1959). After the paper was sent to press, the absolute intensity of the synchrotron beam for $E_{\gamma max} = 22.5$ Mev was measured. It was then possible to compute the yield of protons with energies up to 17 Mev from the (γ, p) reaction on Au^{197}, and this value was found to be $Y = (1.6 \pm 0.9) \times 10^{-5}$ protons/mole-Mev. This value is in good agreement with the results of Dawson,[3] and in poorer agreement with the value obtained by Weinstock and Halpern.[1] The yield of photoprotons from gold, computed by Wilkinson[5] according to the theory of direct resonance emission of nucleons, is in satisfactory agreement with our value.

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