# *PHOTOPROTONS FROM Rh, Pt, AND Pb*

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The angular and energy distributions and the photoproton yields are measured when Rh, Pt, and Pb are irradiated with bremsstrahlung having maximum energies 22.5 and 33.5 MeV. The maxima of the photoproton production cross sections are located at $\gamma$-quantum energies above 22 MeV. In this region $\gamma$-ray absorption by heavy nuclei is mainly of a quadrupole character. The contribution of quadrupole absorption increases with Z.

In our earlier work [1] on the angular and energy distributions of photoprotons from $Pr^{141}$ we noted that it is convenient to investigate the character of $\gamma$-quantum absorption by heavy nuclei in the 20—35 MeV range through measurements of proton-producing reactions. In the present work we measured the angular and energy distributions and the yields of protons from Rh, Pt, and Pb irradiated with bremsstrahlung having maximum energies 22.5 and 33.5 MeV. We wished to determine the role of the quadrupole absorption of $\gamma$ quanta and the position of its maximum.

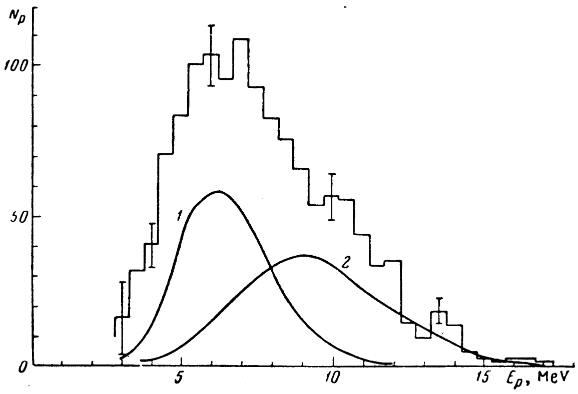


FIG. 1. Energy distribution of 1287 photoprotons from $Rh^{103}$ for $E_{\gamma max}$ = 22.5 MeV. Calculated spectra: curve 1 for evaporated protons; curve 2 for protons from the direct photoeffect.

## EXPERIMENTAL TECHNIQUE AND RESULTS

This work was done using the 35-MeV betatron of the Nuclear Physics Research Institute of Moscow State University. Details of the experimental setup and of the method of measurement have been given in [1]. In the present experiment the photoplates were completely shielded by Plexiglas from the walls of the aluminum vacuum chamber, thus reducing the background considerably. The thin foil targets had the following densities: 25.1 mg/cm$^2$ for Rh, 41.4 mg/cm$^2$ for Pt, and 45.4 mg/cm$^2$ for Pb. The foils were prepared from natural isotope mixtures containing impurities of not more than 0.03% in Rh and Pt, and not more than 0.01% in Pb, so that impurities contributed only a fraction of 1%.

Figures 1—4 show the energy distributions of the photoprotons. A small contribution, evidently only a few per cent, came from deuterons, tritons, and $\alpha$ particles whose tracks were not identified. The background, measured in a target-out run, was taken into account. This background did not

**Table I.** Parameters of curves of $a + b\sin^2\theta\,(1 + p\cos\theta)^2$ and estimated contributions of E2 transitions

| Element | Z | $E_{\gamma max}$, MeV | $E_p$, MeV | a | b | p | $\sigma_{E2}/\sigma_{E1+E2}$, % |
|---|---|---|---|---|---|---|---|
| Rh | 45 | 22.5 | 3.25—9.25 | 97 | 0 | 0 | 0 |
| | | | >9.25 | 28 | 19 | 0.2 | ~1 |
| | | 33.5 | 3.25—9.25 | 49 | 0 | 0 | 0 |
| | | | >9.25 | 14.5 | 16 | 1.2 | ~20 |
| Pt | 78 | 33.5 | 7.25—14.25 | 34.5 | 15.5 | 2.6 | ~60 |
| | | | >14.25 | 3 | 8 | 3.8 | ~75 |
| Pb | 82 | 22.5 | >5.25 | 15.5 | 13 | 1.8 | ~40 |
| | | | >10.25 | 6.5 | 8 | 2.2 | ~50 |

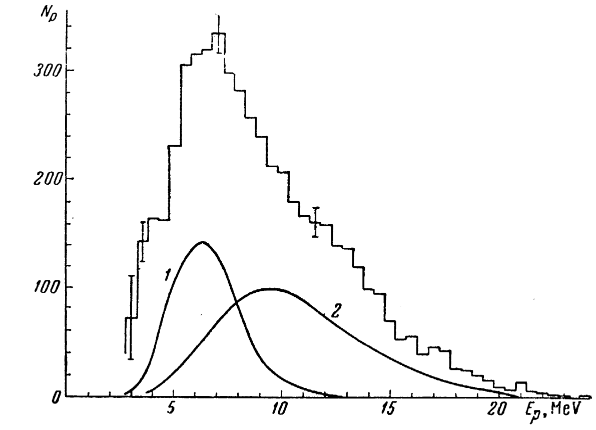


FIG. 2. Energy distribution of 5222 photoprotons from Rh[103] for $E_{\gamma max}$ = 33.5 MeV. Same notation as in Fig. 1.

exceed 5% and was associated mainly with the low-energy portion of the spectrum. At 30° the background was two to three times greater than at other angles.

Figures 5—8 show the angular distributions of the photoprotons, indicating only the statistical errors. The curves through the experimental points represent the formula

$$a + b\sin^2\theta\,(1 + p\cos\theta)^2. \qquad (1)$$

The parameters of these curves are given in Table I. It is known that these curves represent the angular distribution in the case of interference between E1 and E2 absorption, with $p^2/5 = \sigma_{E1}/\sigma_{E2}$. We used this formula to estimate the contribution of quadrupole absorption to the production of protons having different energies (Table I). The approximate character of (1) is shared by these estimates.

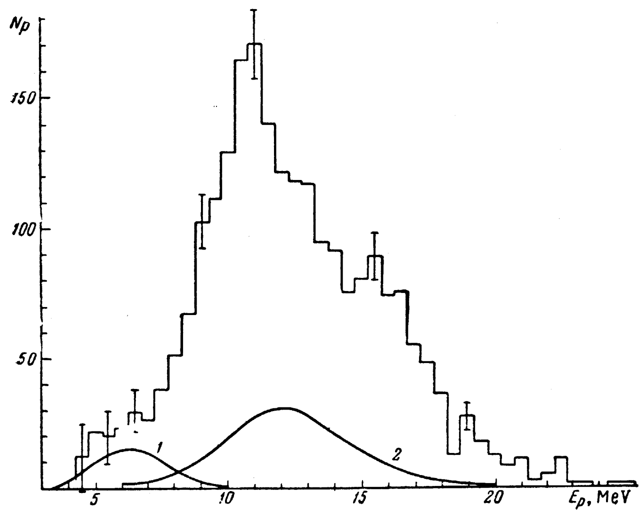


FIG. 3. Energy distribution of 2364 photoprotons from Pt for $E_{\gamma max}$ = 33.5 MeV. Same notation as in Figs. 1 and 2. The scale of curve 1 has been enlarged 50 times.

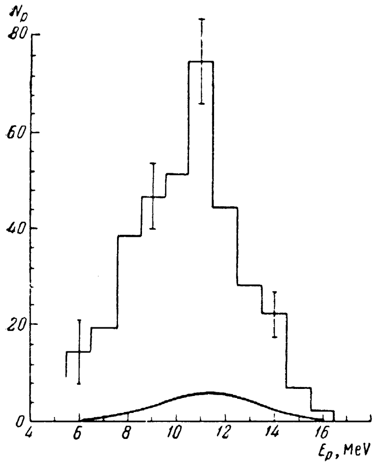


FIG. 4. Energy distribution of photoprotons from Pb for $E_{\gamma max}$ = 22.5 MeV. The smooth curve was calculated for the direct photoeffect.

The photoproton yields were: from Rh, $1.3 \times 10^5$ and $2.8 \times 10^5$ protons/mole-roentgen for $E_{\gamma max}$ = 22.5 MeV and 33.5 MeV, respectively; from Pt, $9.6 \times 10^4$ protons/mole-roentgen for $E_{\gamma max}$ = 33.5 MeV; from Pb, $2.9 \times 10^4$ protons/mole-roentgen for $E_{\gamma max}$ = 22.5 MeV. The errors of these results did not exceed 30%.

## DISCUSSION OF RESULTS

The angular distributions of the photoprotons exhibit a number of interesting regularities. For Rh with $E_{\gamma max}$ = 22.5 MeV they are practically symmetric about 90°, thus indicating the dipole character of γ-quantum absorption in this energy region. A similar pattern has been observed in the irradiation of praseodymium with $E_{\gamma max}$ = 22.5 MeV,[1] tantalum,[2] and gold.[3] However, the angular distribution of photoprotons from lead (Fig. 8) for $E_{\gamma max}$ = 22.5 MeV was strongly asymmetric about 90°; the contribution of quadrupole absorption was ~40%. In the case of lead quadrupole absorption makes its principal contribution to proton

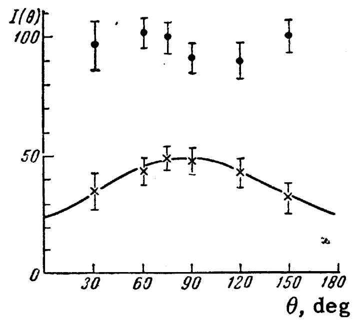


FIG. 5. Angular distributions of photoprotons from Rh[103] for $E_{\gamma max}$ = 22.5 MeV. •—$E_p$ = 3.25–9.25 MeV; ×—$E_p$ > 9.25 MeV.

**Table II.** Measured yields Y of photoprotons from Rh, Pt, and Pb, and estimates based on the evaporation model and on the direct photoeffect

| Element | Rh | | Pt | Pb |
|---|---|---|---|---|
| $E_{\gamma max}$, MeV | 22.5 | 33.5 | 33.5 | 22.5 |
| $Y_{exp}$, protons/mole-roentgen | $1.3\cdot10^5$ | $2.8\cdot10^5$ | $9.6\cdot10^4$ | $2.9\cdot10^4$ |
| $Y_{exp}/Y_{evap}$ | ~3 | ~6 | ~2000 | ~1500 |
| $Y_{exp}/Y_{direct}$ | ~3 | ~4.5 | ~20 | ~11 |

production with $E_p > 10$ Mev; the contribution is considerably smaller when $E_p < 10$ Mev. Similar results have been observed for $Pb^{208}$ [2] and Bi.[4]

An analysis of the angular distributions of photoprotons from Rh and Pt for $E_{\gamma max} = 33.5$ MeV shows that only low-energy protons ($E_p = 3.25–9.25$ MeV) from Rh are isotropic. The high-energy protons from Rh and all protons from Pt are asymmetric about 90°. This indicates a contribution from quadrupole absorption, increasing with A as follows: From ~20% for Rh ($E_p > 9.25$ MeV) to 40—50% for praseodymium [1] and 60—70% for platinum.

The photoproton yields from Rh for $E_{\gamma max} = 22.5$ and 33.5 MeV (Table II) enable us to estimate the contribution from $\gamma$ quanta above 22 MeV when $E_{\gamma max} = 33.5$ MeV. This contribution comprises more than 70% of the total yield; for low-energy protons ($E_p < 9.25$ MeV) it is ~60%, and for high-energy protons ($E_p > 9.25$ Mev) it is of the order of 80%. It follows that the maximum of the photoproton production cross section is to be found above 22 MeV. A similar result has been observed for $Pr^{141}$ [1] and apparently also for Pt (for $E_{\gamma max} = 33.5$ MeV and 22 MeV the yields are $9.6 \times 10^4$ and $2.9 \times 10^4$ protons/mole-roentgen, respectively).[5]

These results agree with the fact that the maxima of all photoproton cross sections for elements with $A > 100$ [6-8] are found in the region $E_\gamma > 20$ MeV.

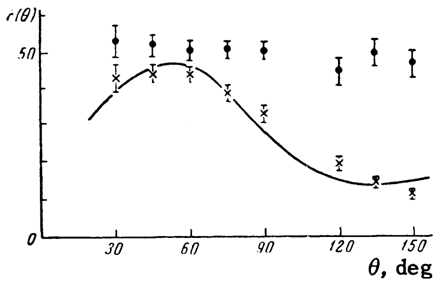


FIG. 6. Angular distributions of photoprotons from $Rh^{103}$ for $E_{\gamma max} = 33.5$ MeV. •—$E_p = 3.25–9.25$ MeV; x—$E_p > 9.25$ MeV.

When the experimental yields are compared with estimates based on the evaporation model and on a direct photoeffect [9] (Table II) we find that neither of these models can account for the results, with the possible exception of those for Rh. Most of the observed photoprotons are produced by the direct resonance absorption of $\gamma$ quanta. The energies of E1 transitions were computed on the single-particle shell model [10] with account of residual interactions determined as in the case of praseodymium.[1] It was found that E1 transition energies do not exceed 20 MeV (15—20 MeV for Rh and 11—16 MeV for Pt and Pb), while the energies of electric quadrupole transitions are considerably higher. For Rh the energies of the principal E2 transitions ($1f_{5/2} \to 1h_{9/2}$; $1f_{7/2} \to 1h_{11/2}$; $2p_{3/2} \to 2f_{7/2}$; $1g_{9/2} \to 1i_{13/2}$ etc.) on the single-particle shell model are ~21—25 MeV. This is in good agreement with experiments indicating the existence of only E1 absorption for $E_\gamma < 22$ Mev and a large contribution of E2 absorption for $E_\gamma > 22$ MeV, especially for high-energy protons. The latter result also agrees with rough estimates of proton energies from E1 and E2 transitions on the single-particle model (for E1 transitions $E_p \approx 2–8$ MeV; for E2 transitions $E_p \sim 10–15$ MeV). In the case of Pt the E2

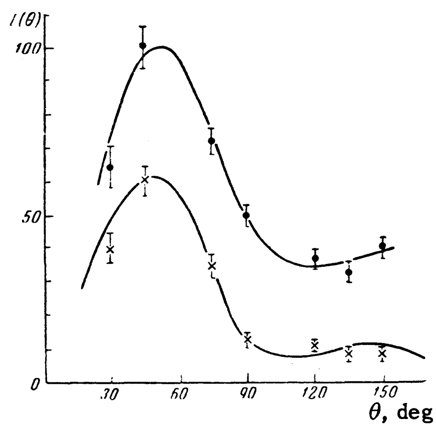


FIG. 7. Angular distributions of photoprotons from Pt for $E_{\gamma max} = 33.5$ MeV. •—$E_p = 7.25–14.25$ MeV; x—$E_p > 14.25$ MeV.

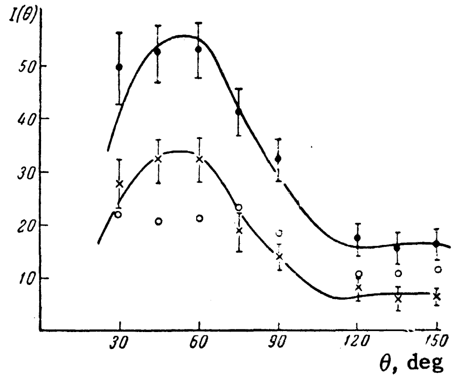


**FIG. 8. Angular distributions of photoprotons from Pb for $E_{\gamma max}$ = 22.5 MeV. o—$E_p$ = 5.25–10.25 MeV; •—$E_p$ > 5.25 MeV; x—$E_p$ > 10.25 MeV.**

transition energy is reduced to ~18—22 MeV, while for Pb it is reduced to 17—21 MeV. This agrees with data indicating strong E2 absorption in Pb for $E_\gamma < 22$ MeV.

A detailed analysis of the photoproton energy distributions is very difficult because it is impossible to take into account the mixing of configurations which are of decisive importance in heavy nuclei.[11] We must also note the following regarding the energy distributions:

1. As Z increases the maximum of the photoproton spectrum is shifted toward higher energies. This is accounted for by the decisive role of the Coulomb barrier, which inhibits low-energy protons from E1 absorption. An increasingly important part is then played by higher-energy protons from E2 absorption.

2. For Rh, as for praseodymium,[1] the maxima of the proton spectra for $E_{\gamma max}$ = 22.5 and 33.5 MeV coincide in position. We note that in[12] the maximum for Rh also remains at 6—7 MeV although irradiation was performed with $E_{\gamma max}$ = 70 MeV. This result, together with the considerable growth of the yield when $E_{\gamma max}$ is increased from 22.5 MeV to 33.5 MeV, indicates that the final nuclei are highly excited.

We therefore conclude that in heavy nuclei the maximum of the photoproduction cross section is located at γ quantum energies not below 20—22 MeV, and that γ-quantum absorption at the maximum is mainly of quadrupole character. With increasing A the maximum for quadrupole absorption is shifted toward lower energies; this is shown by the quadrupole absorption in lead and bismuth for $E_{\gamma max}$ = 22.5 and 24 MeV, respectively.

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[1] V. G. Shevchenko and B. A. Yur'ev, JETP **41**, 1421 (1961), Soviet Phys. JETP **14**, 1015 (1962).
[2] M. E. Toms and W. E. Stephens, Phys. Rev. **98**, 626 (1955).
[3] E. D. Makhnovskiĭ, JETP **38**, 95 (1960), Soviet Phys. JETP **11**, 70 (1960).
[4] M. E. Toms and W. E. Stephens, Phys. Rev. **92**, 362 (1953).
[5] E. V. Weinstock and J. Halpern, Phys. Rev. **93**, 1651 (1954).
[6] Kuo Ch'i-ti and B. S. Ratner, DAN SSSR **125**, 761 (1959), Soviet Phys.-Doklady **4**, 369 (1959).
[7] Carver, Taylor, and Turchinetz, Australian J. Phys. **13**, 617 (1960).
[8] Cameron, Harms, and Katz, Phys. Rev. **83**, 1264 (1951).
[9] E. D. Courant, Phys. Rev. **82**, 703 (1951).
[10] A. Schröder, Nuovo cimento **7**, 461 (1958).
[11] Balashov, Shevchenko, and Yudin, JETP **41**, 1929 (1961), Soviet Phys. JETP **14**, 1371 (1962).
[12] W. K. Dawson, Can. J. Phys. **34**, 1480 (1956).

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