PHOTOPROTONS FROM Rh, Pt, AND Pb

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Submitted to JETP editor October 6, 1961


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 γ-quanta energies above 22 MeV. In this region γ-ray absorption by heavy nuclei is mainly of a quadrupole character. The contribution of quadrupole absorption increases with Z.

In our earlier work[6] on the angular and energy distributions of photoprotons from Pr⁴¹ we noted that it is convenient to investigate the character of γ-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 γ quanta and the position of its maximum.

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[6]. 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/cm² for Rh, 41.4 mg/cm² for Pt, and 45.4 mg/cm² 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 photoprons. A small contribution, evidently only a few per cent, came from deuterons, tritons, and α particles whose tracks were not identified. The background, measured in a target-out run, was taken into account. This background did not

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>E_{γ,max} MeV</th>
<th>E_p MeV</th>
<th>a</th>
<th>b</th>
<th>p</th>
<th>E_{E2} E1 + E2, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rh</td>
<td>45</td>
<td>22.5</td>
<td>3.25-9.25</td>
<td>97</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;9.25</td>
<td>&gt;9.25</td>
<td>28</td>
<td>19</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Pt</td>
<td>78</td>
<td>33.5</td>
<td>7.25-14.25</td>
<td>49</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;14.25</td>
<td>&gt;14.25</td>
<td>14.5</td>
<td>16</td>
<td>1.2</td>
<td>~20</td>
</tr>
<tr>
<td>Pb</td>
<td>82</td>
<td>22.5</td>
<td>&gt;5.25</td>
<td>34.5</td>
<td>15.5</td>
<td>2.6</td>
<td>~60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;10.25</td>
<td>&gt;10.25</td>
<td>8</td>
<td>3.8</td>
<td>2.2</td>
<td>~50</td>
</tr>
</tbody>
</table>
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

\[ a + b \sin^2 \theta (1 + p \cos \theta)^2. \]

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 \( E_{\gamma_{\text{max}}} = 33.5 \text{ MeV} \). 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 \( E_{\gamma_{\text{max}}} = 22.5 \text{ MeV} \). 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 \( E_{\gamma_{\text{max}}} = 22.5 \text{ MeV} \) and \( 33.5 \text{ MeV} \), respectively; from Pt, \( 9.6 \times 10^4 \) protons/mole-roentgen for \( E_{\gamma_{\text{max}}} = 33.5 \text{ MeV} \); from Pb, \( 2.9 \times 10^4 \) protons/mole-roentgen for \( E_{\gamma_{\text{max}}} = 22.5 \text{ MeV} \). 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 \( E_{\gamma_{\text{max}}} = 22.5 \text{ MeV} \) they are practically symmetric about 90°, thus indicating the dipole character of \( \gamma \)-quantum absorption in this energy region. A similar pattern has been observed in the irradiation of praseodymium with \( E_{\gamma_{\text{max}}} = 22.5 \text{ MeV} \), tantalum, and gold. However, the angular distribution of photoprotons from lead (Fig. 8) for \( E_{\gamma_{\text{max}}} = 22.5 \text{ MeV} \) was strongly asymmetric about 90°; the contribution of quadrupole absorption was \( \sim 40\% \). In the case of lead quadrupole absorption makes its principal contribution to proton
Table II. Measured yields \( Y \) of photoprotons from Rh, Pt, and Pb, and estimates based on the evaporation model and on the direct photoeffect

<table>
<thead>
<tr>
<th>Element</th>
<th>Rh</th>
<th>Pt</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\gamma \text{max}} ), MeV</td>
<td>22.5</td>
<td>33.5</td>
<td>33.5</td>
</tr>
<tr>
<td>( Y_{\text{exp}} ) protons/mole-roentgen</td>
<td>( 1.3 \times 10^6 )</td>
<td>( 2.8 \times 10^6 )</td>
<td>( 9.6 \times 10^4 )</td>
</tr>
<tr>
<td>( Y_{\text{exp}}/Y_{\text{evap}} )</td>
<td>( \sim 3 )</td>
<td>( \sim 6 )</td>
<td>( \sim 2000 )</td>
</tr>
<tr>
<td>( Y_{\text{exp}}/Y_{\text{direct}} )</td>
<td>( \sim 3 )</td>
<td>( \sim 4.5 )</td>
<td>( \sim 20 )</td>
</tr>
</tbody>
</table>

production with \( E_p > 10 \text{ MeV} \); the contribution is considerably smaller when \( E_p < 10 \text{ MeV} \). Similar results have been observed for \( \text{Pb}^{208} \) \( [2] \) and \( \text{Bi}^{209} \) \( [4] \).

An analysis of the angular distributions of photoprotons from Rh and Pt for \( E_{\gamma \text{max}} = 33.5 \text{ MeV} \) shows that only low-energy protons (\( E_p = 3.25-9.25 \text{ MeV} \)) 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 \( \sim 20\% \) for Rh (\( E_p > 9.25 \text{ MeV} \)) to 40-50\% for praseodymium \( [1] \) and 60-70\% for platinum.

The photoproton yields from Rh for \( E_{\gamma \text{max}} = 22.5 \text{ and } 33.5 \text{ MeV} \) (Table II) enable us to estimate the contribution from \( \gamma \) quanta above 22 MeV when \( E_{\gamma \text{max}} = 33.5 \text{ MeV} \). This contribution comprises more than 70\% of the total yield; for low-energy protons (\( E_p < 9.25 \text{ MeV} \)) it is \( \sim 60\% \), and for high-energy protons (\( E_p > 9.25 \text{ MeV} \)) 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 \( \text{Pb}^{208} \) \( [1] \) and apparently also for Pt (for \( E_{\gamma \text{max}} = 33.5 \text{ MeV} \) and 22 MeV the yields are \( 9.6 \times 10^6 \) and \( 2.9 \times 10^4 \) protons/mole-roentgen, respectively) \( [1] \).

These results agree with the fact that the maxima of all photoproton cross sections for elements with \( A > 100 \) \( [8-9] \) are found in the region \( E_{\gamma} > 20 \text{ MeV} \).

When the experimental yields are compared with estimates based on the evaporation model and on a direct photoeffect \( [8] \) (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 (\( 1f_{5/2} \rightarrow 1h_{9/2} ; 1f_{7/2} \rightarrow 1h_{11/2} ; 2p_{3/2} \rightarrow 2f_{7/2} ; 1g_{9/2} \rightarrow 1i_{13/2} \) etc.) on the single-particle shell model are \( \sim 21-25 \text{ MeV} \).

This is in good agreement with experiments indicating the existence of only \( E1 \) absorption for \( E_{\gamma} < 22 \text{ MeV} \) and a large contribution of \( E2 \) absorption for \( E_{\gamma} > 22 \text{ MeV} \), 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 \( E_p \approx 2-8 \text{ MeV} \) for \( E2 \) transitions \( E_p \approx 10-15 \text{ MeV} \)). In the case of Pt the \( E2 \)
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We therefore conclude that in heavy nuclei the maximum of the photoproduction cross section is located at \( \gamma \) quantum energies not below 20—22 MeV, and that \( \gamma \)-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 \( E_{\gamma \text{max}} = 22.5 \) and 24 MeV, respectively.

In conclusion we wish to thank T. A. Ivanova, S. M. Kulakova, and T. V. Yudina for assistance in the treatment of the results. We also wish to thank the betatron crew.

9 E. D. Courant, Phys. Rev. 82, 703 (1951).

Translated by I. Emin

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