CROSS SECTIONS FOR PHOTOPROTON REACTIONS IN LEAD

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The total yield curves for the (γ, p) reactions on Pb^{207} and Pb^{208} and the (γ, pn) and (γ, d) reactions on Pb^{208} were determined from measurements of the induced activity. The energy dependence of the total cross section, which has a maximum at 26.5 MeV (6.2 mb), was determined from the yield curve. The contribution of the (γ, pn) and (γ, d) reactions to the total cross section is discussed and the curve for the (γ, p) cross section, which has a maximum at 26.0 MeV (5.7 mb), is separated. The integral cross sections for all reactions and for the (γ, p) reactions, 60 and 55 MeV-mb, respectively, are consistent with the estimates made by the summation rule for quadrupole transitions.[10]

IN studies of the angular and energy distributions and yield of photoprotons from heavy nuclei[1,2] it was observed that the maximum of the photoproton cross section for W, Pt, and Pb nuclei occurs at γ-ray energies $E_\gamma > 22.5$ MeV, and that the cross section in this region is due primarily to the quadrupole absorption of γ rays. The detailed study of the shape of the cross-section curve for such a "quadrupole giant resonance" is of great interest. For this reason, we determined the yield curve for the (γ, p) reaction in lead from measurements of the induced activity at energies up to 33.5 MeV. When the lead is irradiated by γ bremsstrahlung, induced activity can arise as a result of the reactions $Pb^{207}(\gamma, p)Tl^{206}$ (half-life $T_{1/2} = 4.19$ min), $Pb^{208}(\gamma, p)Tl^{207}$ ($T_{1/2} = 4.79$ min), $Pb^{208}(\gamma, pn)Tl^{206}$, $Pb^{208}(\gamma, d)Tl^{206}$, $Pb^{206}(\gamma, 2n)Pb^{204*}$ ($T_{1/2} = 1.13$ h) and $Pb^{206}(\gamma, pn)Tl^{204*}$ ($T_{1/2} = 1.13$ h)

In this experiment, we measured the total activity, from which we subtracted the contribution of the longer-lived isotopes Pb^{204*} and Tl^{204*} determined from the measured decay curves. The activity of Tl^{206} and Tl^{207} was not separated and the measured curve represents the sum of the yields for the (γ, p) reactions in Pb^{207} and Pb^{208} and the (γ, pn) reaction in Pb^{208}. Similar measurements at energies up to 27 MeV were carried out earlier by Cameron et al,[3] but the authors were able to observe only the rising part of the cross-section curve. In the present experiment, the measurements were made with aid of the 35-MeV betatron of the Nuclear Physics Research Institute of the Moscow State University.

The lead samples consisted of 14- and 30-mm dia. disks mounted on a special support at a distance of ~ 50 cm from the betatron target and irradiated in a γ-bremsstrahlung beam of maximum energy variable in steps of 0.5 MeV from 15 to 33.5 MeV. The maximum energy was stabilized within limits of ±30 keV. The irradiated sample was placed between two end-window β counters, which recorded the induced β activity of Tl^{206} and Tl^{207}. Such an arrangement improved the accuracy with which the geometry could be reproduced for repeated measurements. The stability of operation of the recording apparatus was checked with the aid of a standard source and proved to be within ±1%. To obtain the absolute values of the induced activity, we introduced corrections for the geometry, the resolving time of the recording system, absorption and scattering in air and in the counter window, and self-absorption and self-scattering in the sample.[4] All corrections were determined by calculation. The overall error of the absolute β-activity measurements was $\lesssim \pm 20\%$. The γ intensity was measured with a thin-walled ionization chamber calibrated for absolute intensities by means of a thick-walled aluminum chamber.[5] The error in the determination of the relative intensity did not exceed 2—3% and the error in the absolute measurements was no greater than 8—10%.

The measurements at each point of the yield curve were made 7—8 times and the results were averaged. The resulting yield curve is shown in Fig. 1, where the rms measurement errors are shown. Owing to the smallness of the yield, the error at the beginning of the curve is 7—10%, but then decreases to 5—7% in the 20-MeV region, 3—5% in the 25-MeV region, and does not exceed

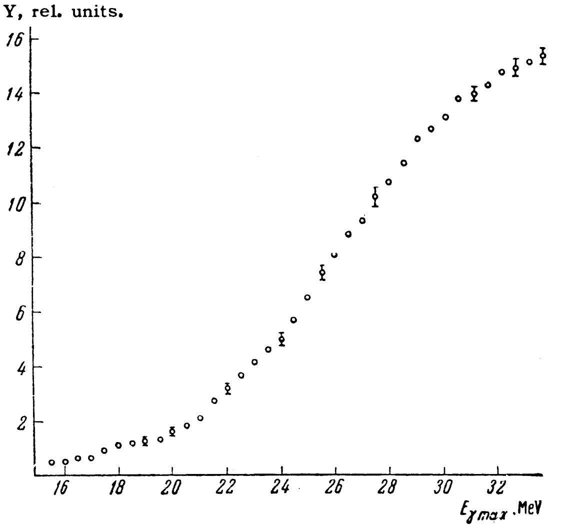

FIG. 1. Total yield of the (γ, p) reactions on Pb^{207} and Pb^{208} nuclei and the (γ, pn) and (γ, d) reactions on Pb^{208}.

2–3% at 30 MeV and above. It should be noted that, although the reaction thresholds for the (γ, p) reaction in Pb^{207} and Pb^{208} are 7.46 and 8.04 MeV, respectively, appreciable induced activity was recorded only for $E_{\gamma max} > 14$–15 MeV. This is consistent with the absence of protons with energies less than 6–7 MeV [1,6] in the energy spectra, which can be explained by the large influence of the Coulomb barrier.

After the usual curve-smoothing procedure for the yield curve, we calculated the energy dependence of the total cross sections for the (γ, p) reactions in Pb^{207} and Pb^{208} and the (γ, pn) and (γ, d) reactions in Pb^{208}. The calculations were performed by the matrix method of Penfold and Leiss. [7] The results are shown in Fig. 2. The total cross section reaches a maximum of 6.2 mb at 26.5 MeV. This is in good agreement with the value obtained by Cameron et al. [3]

For these results, we made certain assumptions on the contribution of the (γ, pn) reaction on Pb^{208} to the total cross section. For the estimates, we

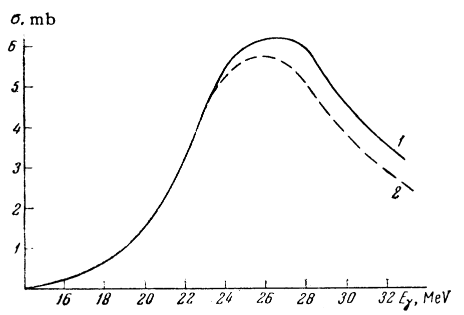

FIG. 2. Cross section of photonuclear reactions in lead: 1 – cross section calculated from the total yield curve, 2 – cross section for the (γ, p) reaction.

assumed that the (γ, pn) reaction takes place mainly through the emission of neutrons by the excited residual nuclei arising after the "evaporation" of protons from the compound nucleus. At the present time, it is known that photoprotons are emitted primarily as a result of the direct resonance absorption of γ quanta and that the energy spectra of photoprotons from heavy nuclei [1,2,6] differ greatly from the "evaporation" protons. Therefore the contribution from the reaction (γ, pn) can be considered to be greatly overestimated in [3]. It is seen from our results [1,2] that the contribution from the (γ, pn) reaction at $E_\gamma < 22$–23 MeV is rather negligible, since protons with $E_p < 6$–7 MeV are almost completely absent in the photoproton spectrum from lead for $E_{\gamma max} = 22.5$ MeV. Comparing the spectra obtained for $E_{\gamma max}$ equal to 22.5 and 33.5 MeV, we note that the number of high-energy protons increases with E_γ. This means that the number of strongly excited residual nuclei, and, along with this, also the contribution from (γ, pn), increase rather slowly. The contribution from the (γ, d) reaction can be neglected for all E_γ. If it is assumed that the contribution from (γ, pn) for $E_\gamma = 33$ MeV is $\sim 40\%$, we can obtain the corrected (γ, p) cross-section curve represented by the dashed curve in Fig. 2. At the maximum, the (γ, p) cross section is ~ 5.7 mb. It is seen that the maximum of the (γ, p) curve is displaced only by ~ 0.5 MeV relative to the maximum of the total cross-section curve, while in the experiment of Cameron et al [3] the maximum of the (γ, p) cross section was displaced by more than 4 MeV.

It is interesting to note that the maximum of the obtained cross-section curves [$E_m \approx 26.5$ MeV for the total cross-section curve and ~ 26 MeV in the case of (γ, p)] turned out to be 12–13 MeV greater than the maximum of the dipole giant resonance. [8,9]

Our earlier estimates [1] of the energy of the basic quadrupole transitions in heavy nuclei from the single-particle model yielded the values ~ 17–21 MeV for lead, i.e., 5–9 MeV lower than the experimental value of E_m. This apparently indicates that in the case of quadrupole transitions, as well as in the case of dipole transitions, the final interactions play an important role.

From the obtained cross-section curves, we calculated the values of the integral cross sections. In the case of all processes under consideration we have

$$\sigma_{int} = \int_0^{33} \sigma dE = 60 \pm 20 \text{ MeV}\cdot\text{mb},$$

while in the case of the specific reaction (γ, p)

$$\sigma_{int} \approx 55 \pm 20 \text{ MeV}\cdot\text{mb}.$$

From these values, we find that the fraction of quadrupole absorption [2] is 50–60%, i.e., ~ 30–40 MeV-mb.

These values can be compared with the approximate value obtained from the expression

$$\int \frac{\sigma_{E2}(E_\gamma)\, dE_\gamma}{E_\gamma^2} = \frac{\pi^2}{5}\left(\frac{e^2}{\hbar c}\right)\left(\frac{1}{mc^2}\right) ZR^2,$$

derived by Khokhlov. [10] If we take E_γ to be constant and equal to 26 MeV, the expression yields

$$\sigma_{int} = \int_0^\infty \sigma_{E2} dE_\gamma \approx 0{,}5 \text{ MeV}\cdot\text{b}.$$

The experimental estimate is consistent with such a value, since a considerable part of the cases of quadrupole excitation of protons as a result of the displacement of the configurations should lead to the emission of neutrons.

In conclusion, we express our gratitude to the betatron crew for aid in the experiment.

[1] V. G. Shevchenko and B. A. Yur'ev, JETP **42**, 707 (1962), Soviet Phys. JETP **15**, 492 (1962).

[2] V. G. Shevchenko and B. A. Yur'ev, JETP **43**, 860 (1962), Soviet Phys. JETP **16**, 609 (1962).

[3] Cameron, Harms, and Katz, Phys. Rev. **83**, 1264 (1951).

[4] I. B. Keirim-Markus and M. A. L'vova, Sb. Issledovanie v oblasti dozimetrii ioniziruyushchikh izlucheniĭ (Collection: Studies in the Dosimetry of Ionizing Radiation) AN SSSR, M. 1957, pp. 3 and 38.

[5] Flowers, Lawson, and Fossey, Proc. Phys. Soc. (London) **65B**, 286 (1952).

[6] M. E. Toms and W. E. Stephens, Phys. Rev. **98**, 626 (1955).

[7] A. S. Penfold and J. E. Leiss, Analysis of Photo Cross Sections, University of Illinois, 1958.

[8] Montalbetti, Katz, and Goldemberg, Phys. Rev. **91**, 659 (1953).

[9] E. G. Fuller and E. Hayward, Proc. of the Int. Conf. on Nuclear Structure, 1960, Kingston, Ontario, Canada, p. 941.

[10] Yu. K. Khokhlov, JETP **32**, 124 (1957), Soviet Phys. JETP **5**, 88 (1957).

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