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CROSS SECTION FOR PHOTOPROTON EMISSION FROM COPPER

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The cross section for photoproton emission from copper is measured from threshold to $E_\gamma = 27$ MeV by directly recording the protons with CsI(Tl) crystals. In contrast to the cross sections measured for other nuclei, the energy dependence of the cross section has a complex shape with maxima at $E_\gamma = 12.5 \pm 0.5$, 16.5 ± 0.5 and 20.5 ± 0.5 MeV. It is suggested that the first two maxima are due to dipole absorption of the quanta by a single proton in the $2p_{3/2}$ state in excess of the $1f_{7/2}$ filled shell corresponding to a magic nucleus with Z = 28.

1. INTRODUCTION

AN experimental investigation of the yield of photoprotons produced by gamma quanta with energy up to 30 MeV in the region of medium and medium-heavy nuclei, including the cases when the emission of a proton occurs without formation of a compound nucleus, has shown that the cross section of the photoproton reactions has one maximum at 20—22 MeV[1-4]. The absence of irregularities in the energy dependence of the cross section corresponding to individual single-particle transitions is apparently due to the strong mixing of the configurations which occurs in this region of nuclei.

On the other hand, such an irregularity was observed in some light nuclei that have one or two nucleons in excess of a closed shell (for example, C^{13}[5]). There are some indications of the existence of preferred transitions, due to nucleons outside the core, also in heavier nuclei such as zinc[6] In this connection we have undertaken an investigation of the yield of photoprotons from the copper nucleus, which has one proton in excess of the closed shell (the magic nucleus of nickel) with Z = 28.

The measurements were made with the P. N. Lebedev Physics Institute synchrotron with maximum gamma ray energy $E_{\gamma m} = 30$ MeV. The protons were registered with CsI(Tl) crystals 0.9 mm thick and 30 mm in diameter, connected by light pipes to an FÉU-29 photomultiplier. The detectors were located in pairs at angles $\theta = 90°$ and $\theta = 135°$ relative to the direction of the gamma beam (Fig. 1). To reduce the proton background, the vacuum chamber was lined on the inside with lead foil.

The principal measurements were carried out with a target of natural copper 40 mg/cm^2 thick. Additional measurements of the yield of the photoprotons as functions of the energy $E_{\gamma m}$, made with a target 13 mg/cm^2 thick, have made it possible to introduce a correction for the target thickness. The dose was determined with a monitor calibrated against a thick-wall aluminum chamber, the sensitivity of which was calculated in the paper by Flowers et al.[7] When measuring the photoproton yield curves, the instant of removal of the high frequency voltage and the form of its drop were chosen in such a way that the stretched beam of duration T ~ 200 μsec coincided in time with the

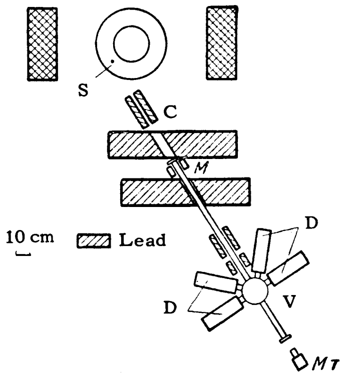

FIG. 1. Arrangement of the apparatus: S–synchrotron target, C–collimator, M–clearing magnet, V–vacuum chamber, M_T–monitor, D–detectors.

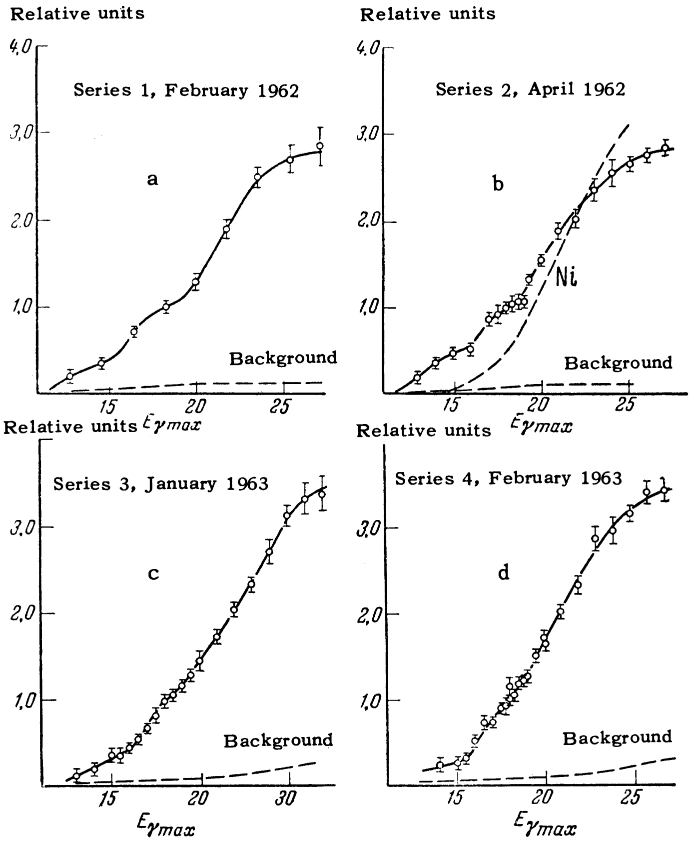

FIG. 2. Yield curves of photoprotons with energy $\epsilon_p > 5$ MeV from copper (mean-square errors are indicated).

gently sloping part of the accelerator magnetic field cycle. Because of this, the uncertainty in the value of the energy $E_{\gamma m}$ did not exceed 2%. The amplitude of the synchrotron magnetic field was maintained accurate to 0.5%.

The accelerator beam energy, which under our conditions was linearly connected with the amplitude of the magnetic field in the gap, was calibrated by measuring the threshold of the reaction Cu^{63} (γ, n) Cu^{62} (E_0 = 10.75 MeV) and the bend in the yield curve of the reaction O^{16} (γ, n) O^{15} at E = 17.25 MeV. Protons with energy $\epsilon_p \geq 5$ MeV were registered. The registration threshold of the analyzer was set by measuring the alpha line from a Po^{210} source (E = 5.3 MeV). It was assumed, in accordance with [8], that in the CsI(Tl) the pulse amplitude is linear in the energy for protons and its plot goes through the origin, and also that the ratio of the efficiencies K of the crystal to alpha particles and to protons is $K(\alpha)/K(p) = 0.5$. The background was determined by measurements without a target (background due to protons) and measurements with an aluminum absorber 270 mg/cm^2 thick (background due to electrons). The total background at $E_{\gamma m}$ = 19 MeV was approximately 8%. To check on the absence of electron superposition, the proton yield was measured at different values of gamma-ray beam intensity. The yield remained constant within the limits of error. In order to reduce the effect of the background and interference, a "cutoff" circuit was installed between the analyzer and the scalar system, so that only the pulses produced during the time intervals corresponding to the stretched gamma-ray beam were registered.

Four series of measurements were made within approximately one year. The measurements were made at 135° in the first two series and at 90 and 135° in the remaining series. There were also some differences in the target location. In the energy interval $E_{\gamma m}$ between 15 and 20 MeV the points are spaced on the average 0.5 MeV apart, and in the intervals $E_{\gamma m}$ = 13–15 MeV and 20–27 MeV they are spaced 1 MeV apart. Each point of a series includes 6–8 measurements. The results are represented by the four yield curves shown in Fig. 2. The proton yield at $E_{\gamma m}$ = 18.0 MeV was taken for unity on each curve. To obtain the absolute values, the most accurate data of series 2 were used. All curves exhibit bends in the region $E_{\gamma m}$ = 16 and 19 MeV. For comparison, Fig. 2b shows the yield of protons from nickel [9], measured under the same conditions as the curve for copper. This result agrees well with the data obtained for nickel by the induced-activity method [10].

Comparison of the yield curves with one another by normalization at $E_{\gamma m}$ = 18.0 MeV shows that the scatter in the curves, particularly at high values of $E_{\gamma m}$, exceeds the mean-square errors of each series. This discrepancy can perhaps be explained by the fact that in series 3 and 4, unlike series 1 and 2, the protons emitted at θ = 90° relative to the gamma-ray beam were also measured. Corrections for angular distribution cannot be made, owing to the lack of detailed data. However, as follows from [11], the angular distribution of protons with energy $\epsilon_p \geq 4$ MeV does not change noticeably with increasing $E_{\gamma m}$. The discrepancy between the normalized curve is more likely due to shortcomings in the relative placement of the monitor and the effective area of the target during the measurements of series 3 and 4. Taking into account the divergence of the curves, we thought it advisable to calculate the cross section curves from the data of each series by the method of Penfold and Leiss. In plotting the cross sections we took account of the fact that the photoproton yield vanishes at $E_{\gamma\ max} = 11.5$ MeV, corresponding to the emission threshold of photoprotons with energy $\epsilon_p \geq 5$ MeV.

The cross section curves obtained are shown in relative units in Fig. 3. As can be seen from this figure, each curve for the cross section of the emission of protons with energy $\epsilon_p \geq 5$ MeV has three pronounced maxima, although a scatter in the positions of the maxima can be noted (up to 1 MeV), and also a scatter in the relative magnitude of the individual peaks.

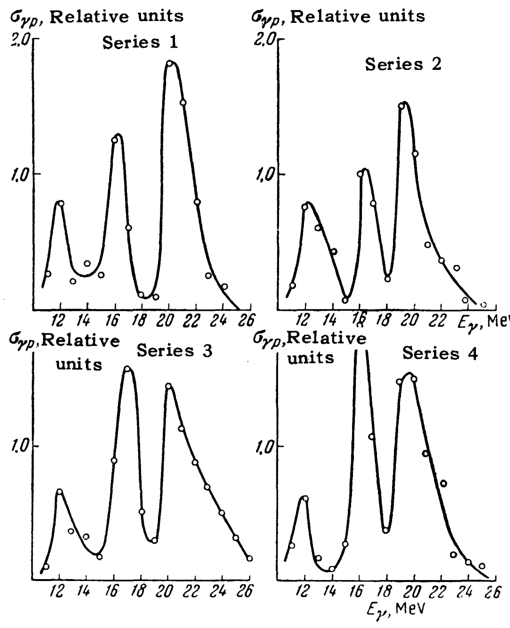

FIG. 3. Curves showing relative cross section for the emission of protons with energy $\epsilon_p \geq 5$ MeV from copper, obtained from the yield curves of Fig. 2.

Figure 4 shows the cross section curve obtained by averaging the curves of Fig. 3. The mean-square errors on the averaged curve correspond to the scatter of the points of the four cross section curves. The three maxima in the emission cross section of the photoprotons with $\epsilon_p \geq 5$ MeV at a gamma-quantum energy E_γ equal to 20.0 ± 0.5, 16.5 ± 0.5, and 12.5 ± 0.5 MeV have integrated cross sections amounting to 64 ± 4, 39 ± 5, and 22 ± 3 MeV-mb, respectively. We assume that the results obtained here are due essentially to the (γ, p) reaction, for when protons with energy $\epsilon_p \geq 5$ MeV are detected the thresholds of registration of photoprotons from the (γ, pn) reaction amount to 21.0 and 22.0 MeV for the isotopes Cu^{63} and Cu^{65}, respectively.

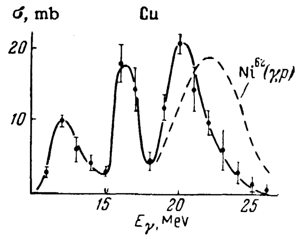

FIG. 4. Cross section for the emission of photoprotons with energy $\epsilon_p \geq 5$ MeV from copper. Dashed curve–cross section of a $Ni^{62}(\gamma, p)$ reaction obtained in [10].

If we disregard the rather crude determination of the dependence of the yield of photoprotons from Cu^{65} on the energy $E_{\gamma m}$ [11], there is at present only one publication devoted to the yield curve of photoprotons from copper [12]. The measurements were made only up to $E_{\gamma m} = 20$ MeV, and only low energy protons, $\epsilon_p < 5$ MeV, were registered. The photoproton emission cross section curve shows a bend at $E_\gamma = 15$ MeV, that is, where the second maximum begins in our measurements. It must be assumed that registration of only the soft part of the photoproton spectrum, as done in [12], increases the contribution of the evaporation protons and can therefore lead to a smearing of the single-particle transition picture. A study of photoprotons from zinc [6] indicates the presence of two peaks in the cross section for the emission of fast protons ($\epsilon_p \geq 9$ MeV).

The cross section obtained in the present work for copper differs essentially in form from the previously measured photoproton cross sections for other nuclei. The form of the cross section curve obtained for fast photoprotons from copper differs from the giant-resonance cross section curve, which has a single maximum, but this is not a contradiction if we recognize that the integral cross section of this reaction is not more than 10% of the integral gamma-ray absorption cross section.

The dashed curve in Fig. 4 is the cross section of the Ni^{62} (γ, p) reaction, measured by Carver and Turchinetz [10] 1). The copper nucleus differs from the nickel nucleus in that it has one proton in excess of the "magic" number (Z = 28). It is natural to assume that the peaks in the cross sec-

1)The cross section has been plotted from the data given in [10] on the width of the resonance curve and on the position of the maximum.

Dipole proton transitions in copper nucleus

Transition	Transition energy, MeV	Transition strength	ε_p, MeV	Penetrability	Probability of proton emission
$1f_{7/2} \to 1g_{9/2}$	17.3	1.09	2.6	$5\cdot10^{-7}$	$1.3\cdot10^{-6}$
$1f_{7/2} \to 1d_{5/2}$	24.1	0.06	9.7	0.12	0.007
$2s_{1/2} \to 2p_{3/2}$	16.1	0.19	−6.2	—	—
$1d_{3/2} \to 1f_{5/2}$	20.9	0.54	−3.5	—	—
$1d_{3/2} \to 2p_{1/2}$	21.9	0.05	−2.5	—	—
$1d_{5/2} \to 2p_{3/2}$	22.5	0.08	−6.3	—	—
$2p_{3/2} \to 2d_{5/2}$	15.3	0.08	8.5	0.10	0.008
$2p_{3/2} \to 3s_{1/2}$	21.3	0.02	13.8	0.22	0.004

tion for copper at $E_\gamma = 12.5$ and 16.5 MeV are due to dipole absorption of quanta by this proton, which is in the $2p_{3/2}$ state. Such a possibility of dipole absorption by a nucleon outside the core was considered by Fujii [13], from whose work it follows, however, that the corresponding peaks for medium and heavy nuclei should lie in the region below the threshold for the (γ, n) and (γ, p) reactions.

We did not measure in the present investigation the energy and angle distributions of the photoprotons. On the basis of the data of [11,14] we can conclude that following the absorption of quanta with 15—19 MeV energy the residual excitation does not exceed 2—3 MeV. The absorption of quanta in the 19—24 MeV region leads to a larger residual excitation, on the order of 6—8 MeV. The anisotropy in the angular distribution of the fast protons decreases with increasing excitation energy. These facts agree qualitatively with the assumption of transitions from the two $p_{3/2}$ shell at low energies and from the $1f_{7/2}$ shell at higher gamma-ray energies. At the same time the energy spectra do not contain maxima that could be ascribed to resonances observed in the cross section, as can be done for example in the case of the oxygen nucleus. We have made a rough estimate of the contributions of the different proton single-particle dipole transitions, similar to what was done earlier in [3]. We used as the basis the level scheme from Schrüder's paper [15]. It was assumed that the center of gravity of the main proton transitions lies in the region of the maximum of giant resonance on copper ($E_\gamma = 18.5$ MeV). The resultant energy scale was used to determine the energies of the different transitions. The transition probabilities were estimated, following Wilkinson [16], with allowance for the penetrability for protons [17]. According to the estimate, only three out of the eight possible transitions can be responsible for the direct proton emission: one from the $1f_{7/2}$ shell and two from the $2p_{3/2}$ shell (see the table). The energies of the corresponding transitions turn out in this case to be 3—5 MeV higher than those experimentally observed.

In conclusion I take the opportunity to express my gratitude to V. P. Lyubimov and N. I. Izotov for help with the work, and also to the synchrotron operating crew. I am most indebted to V. V. Balashov, V. G. Neudachin, and B. A. Tulupov for useful discussion of the results.

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164