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A.I. L'vov, V.A. Petrun'kin, S.G. Popov
and B.B. Wojtsekhowski

POSSIBILITY TO STUDY PHOTON SCATTERING BY PROTON IN THE REACTION $ep \to ep\gamma$

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НОВОСИБИРСК

Possibility to Study Photon Scattering by Proton in the Reaction ep->epγ

A.I. L'vov, V.A. Petrun'kin

P.N. Lebedev Physical Institute
Leninsky Prospect 53, Moscow 117924, USSR

S.G. Popov, B.B. Wojtsekhowski

Institute of Nuclear Physics,
690090, Novosibirsk, USSR

ABSTRACT

A theoretical possibility to determine proton Compton scattering cross section from the reaction $ep\to ep\gamma$ is studied in the kinematics with a small transversal momentum transfer in the electron leg. With the exception of the region of forward photon directions and extreme photon energies close to the maximal ones or zero, registration of the particles γ and p in the final state can enable one to distinguish subprocess of the Compton scattering from the electron bremsstrahlung background and, owing to complete kinematical reconstruction of each individual event, measure in details energy and angular dependence of the γp-scattering cross section. Count rate expected with a storage ring like NEP having the luminosity $L \simeq 2\cdot10^{35}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ as projected is $\approx 10^3$ events/hour. Such measurements might help to determine proton polarizabilities with high statistical accuracy.

1. INTRODUCTION

Photon scattering has served for many years as a very useful tool to study nucleon and nucleus structure at low and intermediate energies. Apart of already common applications for excitation of nucleus levels and giant resonances, recently new possibilities are discussed such as exploration free neutron properties or properties of nucleon and nucleon resonances in the nucleus matter without some distortions caused by initial or final state interactions [1-11]. Arrival of new generation of c.w. electron facilities with energies of few hundred MeV, corresponding tagged photon beams with intensity up to $\approx 10^8\ \mathrm{s}^{-1}$, and application of large crystal γ-detectors of high energy resolution allowing for separation of exclusive final states, puts investigations of γN- and γA-scattering upon far more solid ground. Such investigations are already starting, particularly in Mainz and Saskatoon.

One of the priority problems in the present-day studies of photon scattering by nucleons and nuclei is a more precise measurement of cross sections of the γp-scattering which is the process lying at the ground of understanding and interpreting of photon scattering by nuclei at energies above giant resonances. As an illustration of hardly satisfactory situation with the present experimental knowledge of γp-scattering we can give the following example concerning for an electric polarizability α_p of the proton which is a structure parameter determining ν-dependence of the γp-scattering amplitude and cross section at low photon energies ν [12-14] :

$$\frac{d\sigma(\nu,\vartheta_\gamma)}{d\Omega}_{lab} = \frac{d\sigma^{Born}(\nu,\vartheta_\gamma)}{d\Omega}_{lab} - \frac{\alpha}{M}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'[\alpha_p(1+\cos^2\vartheta_\gamma)+ \tag{1}$$

$$+ 2\beta_p\cos\vartheta_\gamma + O(\nu\nu')],$$

where

$$\frac{d\sigma^{Born}(\nu,\vartheta_\gamma)}{d\Omega}_{lab} = \left(\frac{\alpha}{M}\right)^2\left(\frac{\nu'}{\nu}\right)^2\left\{\frac{1+\cos^2\vartheta_\gamma}{2} + \frac{\nu\nu'}{2M^2}\times\right.$$

$$\times\left[\left(1+2\lambda+\frac{9}{2}\lambda^2+3\lambda^3+\frac{3}{4}\lambda^4\right) - (2+4\lambda+5\lambda^2+2\lambda^3)\cos\vartheta_\gamma +\right.$$

$$\left.\left.+\left(1+2\lambda+\frac{1}{2}\lambda^2-\lambda^3-\frac{1}{4}\lambda^4\right)\cos^2\vartheta_\gamma\right]\right\}. \tag{2}$$

Here M and λ=1.793 are the mass and a.m.m. of the proton, α= = 1/137, ϑ_γ is the photon scattering angle, ν' is the final photon energy,

$$\nu' = \frac{\nu}{1+\frac{\nu}{M}(1-\cos\vartheta_\gamma)}, \tag{3}$$

and β_p is the magnetic proton polarizability. The polarizabilities are obtained from differential cross section of the γp-scattering in the region $\nu \simeq$ 50-130 MeV and ranged from $\alpha_p=(10.7\pm1.1)\cdot10^{-4}$ fm^3 [15] (old data from Moscow) up to $\alpha_p\approx(15\div22)\cdot10^{-4}$ fm^3 (very preliminary data from Mainz [16]) or $\alpha_p=(17\pm3)\cdot10^{-4}$ fm^3 (preliminary data from Illinois [17]). Implying that polarizabilities carry very intimate information about valence quarks and pion cloud of the proton [12, 13] a possibility discussed below to measure with high statistics the γp-scattering cross section in the reaction $ep\to ep\gamma$ seems to be very attractive. This possibility is orientated onto using of internal jet target of the electron storage ring NEP [18].

The low-energy formula (1) predicts that e.g. at ν = = 100 MeV the cross section $d\sigma/d\Omega_{lab}$ (90°) and the ration $\sigma(120^\circ)/\sigma(60^\circ)$ decreases respectively on 13% and 17% when α_p changes from 10 to $15\cdot10^{-4}$ fm^3 (at the fixed sum $\alpha_p+\beta_p$ = $=14.4\cdot10^{-4}$ fm^3 [12]). Hence an obtaining proton polarizabilities is possible from both absolute and relative measurements of angular or energy dependence and the precision $\Delta\alpha_p \le$ $\le 1\cdot10^{-4}$ fm^3 could be reached by measurements of the cross sections within $\le 2\div3\%$. As we will see the expected luminosity $L_e \cong 2\cdot10^{35}$ cm^{-2}s^{-1} of the NEP storage ring is quite sufficient to achieve this aim.

2. KINEMATICS

The process $ep \to ep\gamma$ in the lowest order in α is governed by diagrams in the Fig.1 where notations for 4-momenta are also given. We discuss its kinematics implying that the initial electron beam of the storage ring has a fixed known energy $E = p_o$ and direction labelled as z-axis, and protons from the jet target are almost at rest. Due to conservation of the total 4-momentum,

$$p + P = p' + P' + k, \tag{4}$$

and on-mass-shell constraints,

$$p^2 = p'^2 = m^2, \quad P^2 = P'^2 = M^2, \quad k^2 = 0, \tag{5}$$

where m is the electron mass, among nine values $\vec{p}$, $\vec{k}$, $\vec{P}'$ are independent only five. Therefore, a registration of the photon and recoil proton with measurements of their energies and angles (six values at all) overdetermines the kinematics of the individual event of $ep \to ep\gamma$. Particularly, the relation between the photon energy $\omega = k_o$ and photon direction $\vec{n} = \vec{k}/\omega$,

$$\omega = \frac{2p\,(P-P') + (P-P')^2}{2n\,(p + P - P')}, \tag{6}$$

where

$$n_\mu = (1, \vec{n}) \equiv k_\mu/\omega, \tag{7}$$

allows to refuse oneself from independent measuring of the value ω or use such measurement to define more accurately some angles.

The interesting for us Compton scattering subprocess will dominate when the square of the momentum transfer

$$q = p - p' \tag{8}$$

is small ($\approx m^2$) or, as is evident from

$$Q^2 \equiv -q^2 = Q^2_{min} + 2\,|\vec{p}|\,|\vec{p}'|\,(1 - \cos\vartheta_e) \approx$$

$$\approx Q^2_{min} + \frac{E}{E'}\,\vec{p}_\perp'^{\,2}, \tag{9}$$

when the transversal final electron momentum $\vec{p}'_\perp$ is small. Here

$$Q^2_{min} \equiv 2EE' - 2|\vec{p}|\,|\vec{p}'| - 2m^2 \simeq \frac{(E-E')^2}{EE'}\,m^2 \tag{10}$$

is the minimal momentum transfer squared achieved at forward direction of the outgoing electron. Under this condition the kinematics for the subprocess of scattering of quasi real photon γ^* with the energy

$$\nu = E - E' \tag{11}$$

is almost the same as in the case of real photons of the energy ν flying along z-axis. Particularly, the energy of the scattered photons ω, kinetic energy of the recoil protons T_p and their polar angle ϑ_p will be close respectively to

$$\omega^{real} = \nu' \quad \text{(see (3))}, \tag{12}$$

$$T_p^{real} = \nu - \nu' = \frac{\nu\nu'}{M}\,(1 - \cos\vartheta_\gamma), \tag{13}$$

$$\left(\cot a n \frac{\vartheta_p}{2}\right)^{real} = -\left(1 + \frac{\nu}{M}\right) \tan \frac{\vartheta_\gamma}{2} . \quad (14)$$

These formulae determine the mutual positions of the γ- and p-detectors needed to observe the Compton scattering on the proton.

3. ESTIMATIONS OF THE CROSS SECTIONS

Under the same condition of small Q^2 the cross section of the process $ep \to ep\gamma$ determined by the diagram 1a is given by the formula

$$d\sigma^{(a)} \simeq dN\ (\nu,\ Q^2)\ \frac{d\sigma_{\gamma^* p \to \gamma p}(\nu, \vartheta_\gamma)}{d\Omega_{lab}}\ d\Omega_\gamma\ , \quad (15)$$

and proportional to the differential cross section of the $\gamma^* p \to \gamma p$ scattering with real initial photons. Here dN is the equivalent photons flux [19] :

$$dN(\nu, Q^2) = \frac{\alpha}{\pi} \frac{d\nu}{\nu} \frac{dQ^2}{Q^2} \left[\left(1 - \frac{\nu}{E}\right) \left(1 - \frac{Q^2_{min}}{Q^2}\right) + \frac{\nu^2}{2E^2} \right] \quad (16)$$

or, integrated over Q^2,

$$dN(\nu) = \frac{\alpha}{\pi} \frac{d\nu}{\nu} \left[\left(1 - \frac{\nu}{E} + \frac{\nu^2}{2E^2}\right) \log \frac{Q^2_{max}}{Q^2_{min}} - \left(1 - \frac{\nu}{E}\right) \left(1 - \frac{Q^2_{min}}{Q^2_{max}}\right) \right] \quad (17)$$

where Q^2_{max} is a cut-off imposed on event selection.

If the photon angle ϑ_γ and photon energy are not very small, then the 4-momentum transfer squared carried out by the virtual photon in the diagram 1b and determined by the recoil proton energy,

$$-q'^2 \equiv -(P - P')^2 = 2M \cdot T_p\ , \quad (18)$$

will be high, $\gg m^2$, and the electron bremsstrahlung contribution will be suppressed. Neglecting the proton recoiling, the bremsstrahlung cross section is given by the well-known Bethe-Heitler formula [20] which in the case of small electron angles $\vartheta_e^2 \ll \vartheta_\gamma^2$ is reduced to

$$d\sigma^{(b)}(\vartheta_e = 0) = \frac{\alpha^3}{4\pi} \left(1 - \frac{\nu}{E} + \frac{\nu^2}{2E^2}\right) \frac{d\nu}{\nu^3} \frac{dQ^2}{E\ (E-\nu)} \frac{1+\cos \vartheta_\gamma}{(1-\cos \vartheta_\gamma)^3}\ d\Omega_\gamma\ , \quad (19)$$

so that its ratio to the cross section (15),(1) is equal to

$$R \equiv \frac{d\sigma^{(b)}}{d\sigma^{(a)}} \approx \frac{M^2 Q^2}{2\nu^2 E\ (E-\nu)} \frac{1+\cos \vartheta_\gamma}{(1+\cos^2 \vartheta_\gamma)(1-\cos \vartheta_\gamma)^3} \simeq$$

$$\simeq \frac{2M^2}{\nu^2} \frac{1+\cos \vartheta_\gamma}{(1+\cos^2 \vartheta_\gamma)(1-\cos \vartheta_\gamma)^3} \sin^2 \left(\frac{\vartheta_e}{2}\right). \quad (20)$$

At ν=100 MeV and $\vartheta_\gamma = 90^\circ$ this ratio is less than 1 at electron angles up to $\vartheta_e \simeq 9^\circ$ what corresponds to $Q \simeq 20$ MeV at E=200 MeV (the NEP energy), see Fig. 2. The condition $R < 1$ represents the main requirement for event selection which must be fulfilled to observe the proton Compton scattering. When the photon energy ν is small or close to maximal one or at small photon angle ϑ_γ , this requirement cannot be realized because of finite resolution of experimental set-up.

To estimate count rates it is useful to calculate also the cross sections $d\sigma/d\nu \cdot d\Omega_{\gamma}$ integrated over Q up to some cut-off Q_{max}. These cross sections found with (15),(17),(19) and (21) are depicted in the Fig.3. Typical value of the cross section $\sigma^{(a)}$ is $\approx 10^{-36}$ cm^2/MeV/sr so that with the projected NEP luminosity $L_e \simeq 2 \cdot 10^{35}$ cm^{-2}s^{-1} and γ-detector aperture $\Delta\Omega_{\gamma} \simeq 0.1$ sr the expected count rate will be $\approx 10^3$ events/hour per 10-MeV photon energy interval.

To obtain estimations free from equivalent photon approximation, neglecting of proton recoil and interference of the diagrams 1a and 1b, we analyzed also a simple model with spinless charged particles convenient for fast Monte-Carlo simulations (see Appendix). The computations within this model showed that the relation (20) between the cross sections $\sigma^{(a)}$ and $\sigma^{(b)}$ is still valid after taking into account the recoiling. The interference term is only $\simeq$ 10-20% of the cross section $\sigma^{(b)}$ itself. This analysis says that the equivalent photon approximation overestimates the cross section $\sigma^{(a)}$ on 15-20%. Therefore a final procedure for obtaining Compton cross sections and proton polarizabilities from the $ep \to ep\gamma$ data must be based on more accurate theoretical models than (15). Such models can be certainly developed on the ground of calculations [21] of the reaction $ep \to ep\gamma$ fulfilled for spin 1/2 particles and model-free low-energy expansion of the $\gamma^* p \to \gamma p$ subprocess amplitude with virtual photons followed from a general phenomenological description

of polarizable particles [14]. An expected accuracy of such models seems to be quite sufficient to allow a precise determination of the proton polarizabilities.

4. CONCLUSION

The above estimations argue that a study of the reaction $ep \to ep\gamma$ with the final γ and p-coincidences at internal jet targets of electron storage rings provides an attractive possibility for obtaining high statistics data on γp-scattering and proton polarizabilities. Such possibility might be realized at the Novosibirsk storage ring NEP covering the energies up to $\nu \approx 200$ MeV. The realization will require detectors with the energy resolution ≤5% (at least for protons) and space resolution sufficient for determination of γ and p angles within ≤ 2-3° to be able, as the result, to control the balance of transversal momenta of these two particles within $|\vec{k}_{\perp} + \vec{P}'| \leq$ 5-10 MeV.

Comparing this proposal with more traditional methods for studying Compton scattering it should be marked that a registration and spectrometry of the recoil protons with low energies ≈ 10 MeV becomes be possible owing to very thin target (gas jet). Together with the registration of photons it allows to reconstruct all energies and thereby to have the same advantages as with tagged photons. At the same time the refusal from registration of final electrons enables one to work with the whole intensity of the internal electron beam of the storage ring thus achieving an effective luminosity in the $\gamma^* p$-collisions $L_\gamma \geq 10^{33}$ $cm^{-2}s^{-1}$, that is far beyond possibilities of the tagged photon method, and achieving yields $\approx 10^3$ events/hour.

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APPENDIX. Scalar Model

In this model both electrons and protons are considered as spinless point-like particles so that Compton scattering block is described by diagrams in the Fig.4. Corresponding γp-scattering cross section looks like

$$\frac{d\sigma(\nu,\vartheta_\gamma)}{d\Omega_{lab}} = \left(\frac{\alpha}{M}\right)^2 \left(\frac{\nu'}{\nu}\right)^2 \frac{1+\cos^2\vartheta_\gamma}{2} \qquad (21)$$

and within 10 to 20% agrees with the real value of the cross section at energies up to $\nu \simeq 100 - 130$ MeV [15,16] where Δ-resonance does not dominate yet.

The scalar model rather well describes also equivalent photons spectrum and electron bremsstrahlung radiation off heavy proton for forward directions of outgoing electrons,

with the exception of ν close to the maximal value E, yielding instead of (16) and (19) respectively

$$dN\,(\nu, Q^2) = \frac{\alpha}{\pi}\frac{d\nu}{\nu}\frac{dQ^2}{Q^2}\left(1 - \frac{\nu}{E}\right)\left(1 - \frac{Q^2_{min}}{Q^2}\right) \qquad (22)$$

and

$$d\sigma^{(b)}(\vartheta_e=0) = \frac{\alpha^3}{4\pi}\left(1 - \frac{\nu}{E}\right)\frac{d\nu}{\nu^3}\frac{dQ^2}{E(E-\nu)}\frac{1+\cos\vartheta_\gamma}{(1-\cos\vartheta_\gamma)^3}\,d\Omega_\gamma\,. \qquad (23)$$

Amplitudes of the processes shown in the diagrams 1a and 1b, in the frame of the model, are

$$T^{(a)} = 2e^3\,\varepsilon^*_\mu\,V^{(a)}_\mu,$$
$$T^{(b)} = -2e^3\,\varepsilon^*_\mu\,V^{(b)}_\mu, \qquad (24)$$

where $e = \sqrt{4\pi\alpha}$, ε_μ is the final photon polarization (εk=0) and

$$V^{(a)}_\mu = \frac{(p+p')_\nu}{(p-p')^2}\left[g_{\mu\nu} + \frac{P_\mu P'_\nu}{Pk} - \frac{P_\nu P'_\mu}{P'k}\right],$$
$$V^{(b)}_\mu = \frac{(P+P')_\nu}{(P-P')^2}\left[g_{\mu\nu} + \frac{p_\mu p'_\nu}{pk} - \frac{p_\nu p'_\mu}{p'k}\right]. \qquad (25)$$

Total amplitude squared summarized over photon polarizations,

$$|T|^2 = -4\,(4\pi\alpha)^3\left[V^{(a)}_\mu - V^{(b)}_\mu\right]^2, \qquad (26)$$

is determined by components of the 4-vectors $V^{(a)}$ and $V^{(b)}$ which in turn are easy computed from (25) in terms of particles 4-momenta.

A differential cross section of the reaction *ep->epγ*,

$$d\sigma = \frac{1}{4M|\vec{p}|}\frac{|T|^2}{(2\pi)^5}\delta^4(p+P-p'-P'-k)\frac{d^3p'}{2E'}\frac{d^3P'}{2P'_0}\frac{d^3k}{2\omega}, \quad (27)$$

is recasted in terms of the variables ν, Q^2, Ω_γ as

$$d\sigma = \frac{1}{4M|\vec{p}|}\frac{|T|^2}{(2\pi)^5}\frac{d\nu\, dQ^2\, d\phi_e}{4|\vec{p}|}\frac{\omega^2 d\Omega_\gamma}{2\,(2M\nu - Q^2)}, \quad (28)$$

where ϕ_e is the azimuth angle of the final electron which, together with the energy $E' = E - \nu$ and the polar angle ϑ_e,

$$\sin^2\left(\frac{\vartheta_e}{2}\right) = \frac{1}{4|\vec{p}||\vec{p}'|}(Q^2 - Q^2_{min}), \quad (29)$$

fixes the 4-vectors p' and $q=p-p'$. Owing to the momentum conservation (4) the direction of photon $\vec{n}$ determines the photon energy

$$\omega = \frac{q\,(2P+q)}{2n\,(Q+q)} = \frac{M\nu - Q^2/2}{M + \nu - \vec{n}\,(\vec{p} - \vec{p})} \quad (30)$$

and thereby the 4-momenta k and $P' = q + P - k$ completing the reconstruction of the kinematics. The remaining integrations over ϕ_e or Q^2 in (28) are easy carried out numerically.

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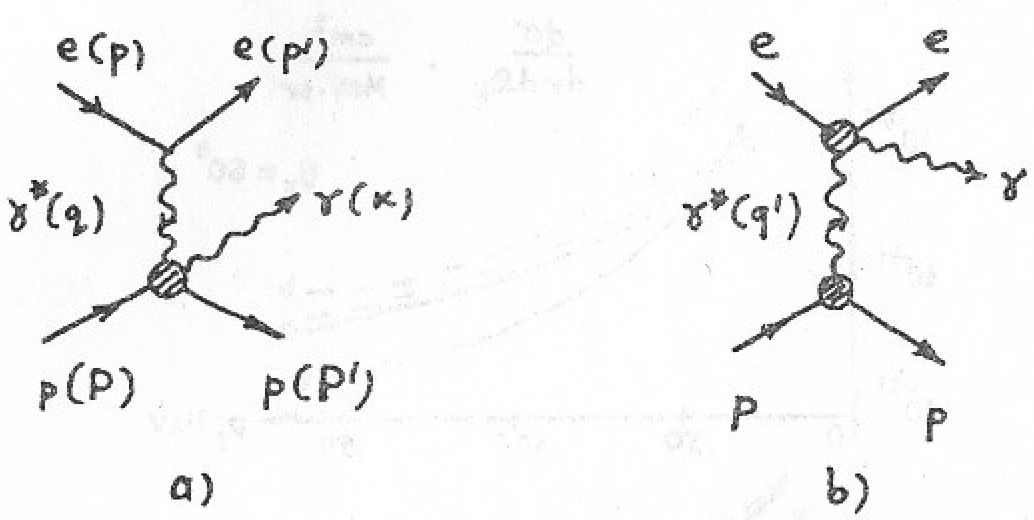

Fig. 1. Mechanisms of the reaction *ep* -> *epγ* : *a)* subprocess of photon scattering by proton; *b)* electron large angle bremsstrahlung.

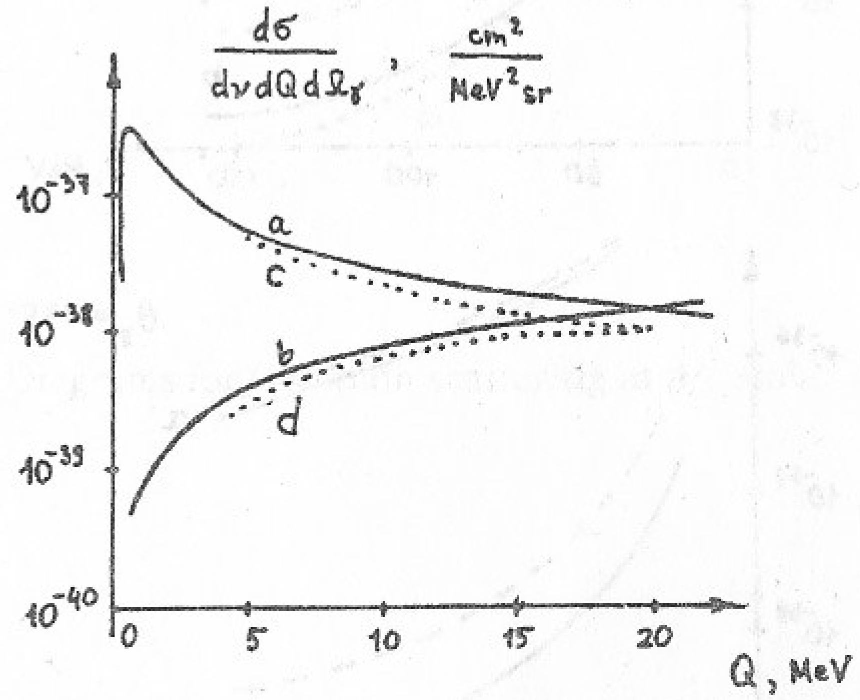

Fig. 2. Q-dependence of the proton Compton scattering contribution (15) (curve *a)* and electron bremsstrahlung (19) (curve *b)* at $E=200$ MeV, $\nu = 100$ MeV, $\vartheta_\gamma = 90°$. Dot curves present the results in the scalar model for photon radiation by electron (curve *c)* and proton (curve *d)*.

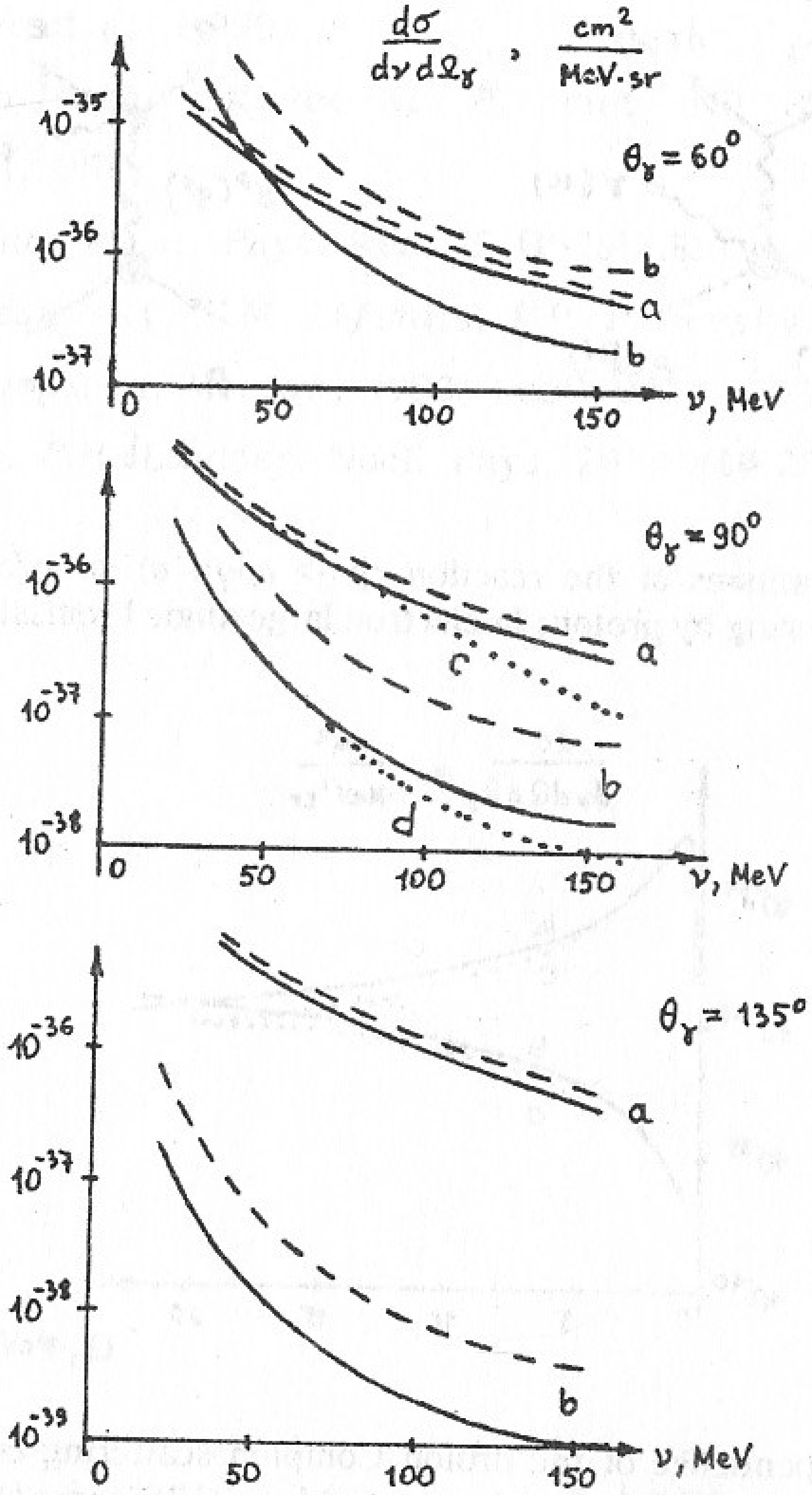

Fig. 3. Cross sections for the reaction $ep \to ep\gamma$ at cut-off $Q_{max} = 10$ MeV (solid lines) and $Q_{max} = 20$ MeV (dashed lines). Labels *a)* and *b)* refer to the diagrams 1*a* and 1*b* contributions, (15) and (19), respectively. $E = 200$ MeV. Dot curves present the cross sections in the scalar model with cut-off $Q_{max} = 10$ MeV for photon radiation by electron (curve *c*) and proton (curve *d*).

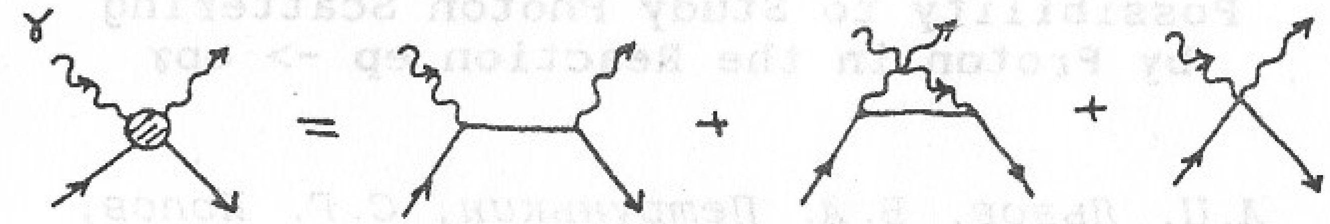

Fig. 4. Diagrams for Compton scattering in the scalar model.

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А.И. Львов, В.А. Петрунькин, С.Г. Попов, Б.Б. Войцеховский

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