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CHARGED PAIR PRODUCTION BY PHOTON SCATTERING ON A PROTON

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We have investigate the production of lepton and pseudoscalar meson charged pairs by high energy linearly polarized photon–proton scattering in the point–like approximation. The corresponding azimuthal and polar angle distributions on a recoil proton in the inclusive experimental setup have been calculated. The asymmetry $\Lambda_{\rm tot}$ has the values from 0.02 at small values of the polar angle θ up to 0.05 for $\theta \sim \pi/2$.

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1. *Introduction*

In this work we suggest the method of measuring the recoil proton distributions which can provide an independent way to control the luminosity and polarization properties of a photon beam. In our considerations, we start with the processes of charged pair $a\bar{a}$ (e^+e^-, $\mu^+\mu^-$and $\pi^+\pi^-$) production,

$$\gamma(k,\varepsilon) + \mathrm{p}(p) \to a(q_-) + \bar{a}(q_+) + \mathrm{p}(p')\,,$$

$$s = 2k.p, \quad k^2 = 0, \quad p^2 = (p')^2 = M^2, \quad q_-^2 = q_+^2 = m^2, \tag{1}$$

by high-energy photon scattering on a proton. It is supposed that an initial proton is at rest, while the recoil proton is detected. All considered leptons and pions are supposed to be point–like particles. One must consider two different mechanisms of pair production for such processes. One corresponds to the pair creation by two photons (Bethe–Heitler (BH)) and the second one is the bremsstrahlung (B), which corresponds to the case when a pair is created by a single virtual photon. The contribution of the B type is suppressed compared with one of the BH type by the factor $|q^2|/s$, and the interference of B and BH amplitudes is exactly zero for the recoil proton in the inclusive setup.

It must be said that in our calculations we use the lowest-order contributions in the QED coupling constant α. Moreover, the accuracy of the formulae given below is determined by the terms we have omitted systematically compared with terms of the order of unity,

$$1 + O(\frac{\alpha}{\pi}, \frac{|Q^2|}{s}, \frac{m^2}{s}, \frac{M^2}{s}), \quad Q = p - p'. \tag{2}$$

For the considered processes, we work in the peripheral kinematical region $s \gg |q^2| \sim M^2$, where the Sudakov [3] parametrization of transferred momentum and the 4–momenta of final particles are effective,

$$Q = \alpha_q \tilde{p} + \beta_q k + q_\perp, \quad q_\pm = \alpha_\pm \tilde{p} + x_\pm k + q_{\pm\perp}, \tag{3}$$

$$c_\perp p = c_\perp k = 0, \quad \tilde{p} = p - k\frac{M^2}{s}, \quad \tilde{p}^2 = 0, \quad q_\perp^2 = -\boldsymbol{q}^2 < 0.$$

The on the mass shell condition for the recoil proton $(p-q)^2 = M^2$ gives the approximation for $s\beta_q$

$$s\beta_q = -(\boldsymbol{q}^2 + M^2\alpha_q)/(1-\alpha_q) \approx -\boldsymbol{q}^2. \tag{4}$$

Here we use the fact that $M^2\alpha_q = (M^2/s)(s_1 + \boldsymbol{q}^2)$ is much smaller than $\boldsymbol{q}^2$, where $s_1 = (q_+ + q_-)^2$ is the invariant mass square of the pair, assumed to be of order $4m^2$. In the case of large Q, one can put the term $Q^2 = s\alpha_q\beta_q - \boldsymbol{q}^2$ equal to $Q^2 = -\boldsymbol{q}^2 = -q^2$.

The relation, first mentioned in a paper of Benaksas and Morrison [1],

$$\tan\theta = \frac{\boldsymbol{p}'_\perp}{\boldsymbol{p}'_{||}} = \frac{|\boldsymbol{q}|}{(\boldsymbol{q}^2/2M)} = \frac{2M}{q}\,, \tag{5}$$

which is in fact the ratio of the transversal and longitudinal components of momentum of the recoil proton (laboratory frame is implied) can be written in a different form [2] in terms of the value of the 3–vector of momentum of recoil proton P,

$$\frac{P}{2M} = \frac{\cos\theta}{\sin^2\theta}, \quad q^2 = 4M^2\cot^2\theta, \tag{6}$$

where θ is the angle between the directions of initial photon and recoil proton in the laboratory frame.

The matrix element of the charged lepton or pion pair production in the lowest order of QED perturbation theory (keeping in mind BH mechanism) has the form

$$M^i = \frac{(4\pi\alpha)^{3/2}}{-\,q^2} J^p_\nu O^i_{\mu\lambda} \varepsilon^\lambda(k) g^{\mu\nu}, \quad i = l(\mathrm{e},\mu), \pi, \tag{7}$$

where the proton current is defined as

$$J^p_\nu = \bar{u}(p') \left[F_1(Q^2)\gamma_\nu + \frac{[\hat{Q}, \gamma_\nu]}{4M} F_2(Q^2) \right] u(p),$$

and $F_{1,2}$ are the proton form factors. The Compton lepton tensor has the form

$$O^l_{\mu\lambda} = \bar{u}(q_-) \left[\gamma_\mu \frac{\hat{q}_- - \hat{Q} + m}{D_+} \gamma_\lambda + \gamma_\lambda \frac{\hat{Q} - \hat{q}_+ + m}{D_-} \gamma_\mu \right] v(q_+),$$

and similarly for the Compton pion tensor

$$O^\pi_{\mu\lambda} = -2g_{\mu\lambda} + \frac{(2q_- - k)_\lambda (Q - 2q_+)_\mu}{D_-} + \frac{(k - 2q_+)_\lambda (2q_- - k)_\mu}{D_+} \,,$$

where $D_\pm = (k - q_\pm)^2 - m^2$. These tensors obey the gauge invariance requirements $O^i_{\mu\lambda} Q^\mu = O^i_{\mu\lambda} k^\lambda = 0$.

One can write the matrix element (7) using the Gribov prescription for the Green function of the virtual photon in Feynman gauge

$$g^{\mu\nu} = g^{\mu\nu}_\perp = \frac{2}{s} \left[\tilde{p}^\mu k^\nu + \tilde{p}^\nu k^\mu \right] \approx \frac{2}{s} \tilde{p}^\mu k^\nu,$$

in the form

$$M^i = s \frac{(4\pi\alpha)^{3/2}}{-\,q^2} N^p \frac{2}{s} \tilde{p}^\mu e^\lambda O^i_{\mu\lambda}, \quad N^p = \frac{1}{s} J^p_\eta k^\eta, \quad i = l(\mathrm{e},\mu), \pi, \tag{8}$$

where the factor s is extracted explicitly.

Both light–cone projections of the proton current as well Compton tensors are finite in the large s limit. Summing over the spin states of the proton, one obtains for the proton current projection square

$$\sum |N^p|^2 = 2F(q^2) = 2 \left[F_1^2(-q^2) + \frac{q^2}{4M^2} F_2^2(-q^2) \right].$$

Expressing the phase volume of the final particles in terms of the Sudakov variables [3], one has

$$\mathrm{d}\Gamma = (2\pi)^{-5} \frac{\mathrm{d^3q_-}}{2\epsilon_-} \frac{\mathrm{d^3q_+}}{2\epsilon_+} \frac{\mathrm{d^3p'}}{2\mathrm{E'}} \delta^4(\mathrm{p + k - p' - q_- - q_+}) = (2\pi)^{-5} \frac{\mathrm{d^2qd^2q_-dx_-}}{\mathrm{4sx_-x_+}}, \tag{9}$$

where the unit factor $\mathrm{d}^4\mathrm{Q}\delta^4(\mathrm{p}-\mathrm{Q}-\mathrm{p}')$ was introduced. Besides this, one must use the following relation

$$\frac{\mathrm{d}^3\mathrm{q}_-}{2\epsilon_-} = \mathrm{d}^4\mathrm{q}_-\delta(\mathrm{q}_-^2-\mathrm{m}^2) = \frac{\mathrm{s}}{2}\mathrm{d}^2\mathrm{q}_-\mathrm{d}\alpha_-\mathrm{dx}_-\delta(\mathrm{s}\alpha_-\mathrm{x}_- - \boldsymbol{q}_-^2-\mathrm{m}^2).$$

Next, we do the straightforward operation of the calculation of the cross section, i. e. the summation over the spin states of the leptons of square of the matrix element, the integration over the energy fractions of the pair x_- and x_+, $(x_-+x_+=1)$ and its transversal momentum $\mathrm{d}^2\boldsymbol{q}_-$, (the conservation law implies $\boldsymbol{q}_-+\boldsymbol{q}_+=\boldsymbol{q}$). With the use of the photon polarization matrix $\varepsilon_i\varepsilon_j^* = (1/2)\big[I+\xi_1\sigma_1+\xi_3\sigma_3\big]_{ij}$, ($\xi_{1,3}$ are the Stokes parameters, I is the unite matrix, and σ_i are the Pauli matrices), the result can be written in the form

$$\frac{\mathrm{d}\sigma^{\gamma\mathrm{p}\to\mathrm{a^i\bar{a}^ip}}}{\mathrm{d}\varphi\mathrm{d}\theta} = \frac{1}{2\pi}\frac{\mathrm{d}\sigma_0^{\gamma\mathrm{p}\to\mathrm{a^i\bar{a}^ip}}}{\mathrm{d}\theta}\big(1+\Lambda^i(\xi_1\sin2\varphi+\xi_3\cos2\varphi)\big). \tag{10}$$

The azimuthal angle φ is the angle between the two vectors transversal to the photon direction, i.e. the linear polarization $\boldsymbol{\varepsilon}$ of the photon and $\boldsymbol{q}$, and

$$\frac{\mathrm{d}\sigma_0^{\gamma\mathrm{p}\to\mathrm{a^i\bar{a}^ip}}}{\mathrm{d}\theta} = \frac{\alpha^3}{3\pi M^2}F(q^2)\frac{\sin\theta}{\cos^3\theta}\,a^i, \quad \text{where} \tag{11}$$

$$a^l = \frac{4L_l}{R_l}+1-\frac{m_l^2L_l}{M^2R_l}\tan^2\theta, \quad a^\pi = \frac{1}{2}\left(\frac{2L_\pi}{R_\pi}-1+\frac{m_\pi^2L_\pi}{M^2R_\pi}\tan^2\theta\right),$$

and Λ^i is the azimuthal asymmetry

$$\Lambda^i = \frac{b^i}{a^i}, \quad b^l = -(1-\frac{m_l^2L_l}{M^2R_l}\tan^2\theta), \quad b^\pi = \frac{1}{2}(1-\frac{m_\pi^2L_\pi}{M^2R_\pi}\tan^2\theta)\,. \tag{12}$$

In Eqs. (11, 12), the quantities L_i, R_i are

$$R_i = \sqrt{1+\frac{m_i^2}{M^2}\tan^2\theta}, \ \ L_i = \ln\left(\frac{M}{m_i}\right)+\ln\cot\theta+\ln(1+R_i)\,.$$

It is interesting to consider the distribution $\mathrm{d}\sigma^{\gamma\mathrm{p}\to\mathrm{a^i\bar{a}^ip}}/\mathrm{dq}$ of the recoil proton over the value of q (Fig. 1). Calculations of this distribution were carried out on the

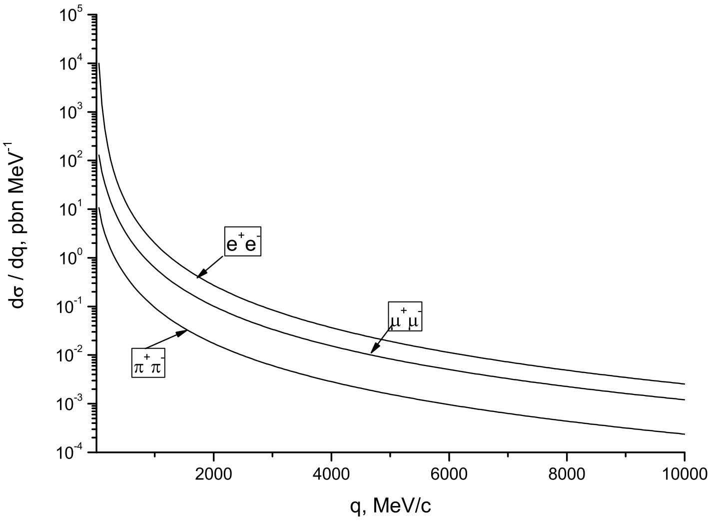

Fig. 1. The distributions $\mathrm{d}\sigma^{\mathrm{i}}/\mathrm{dq}$ *in units of* pbn MeV^{-1} *for the cases of* $\mathrm{e}^+\mathrm{e}^-$*pair,* $\mu^+\mu^-$*pair and* $\pi^+\pi^-$*pair production as functions of* q*.*

base of the formula, which is obtained from (10, 11) after the substitution $\theta = \arctan(2M/q)$ (see Eq. (6))

$$\frac{\mathrm{d}\sigma^{\gamma\mathrm{p}\to\mathrm{a^i\bar{a}^i p}}}{\mathrm{dq}} = \frac{8\alpha}{3q^3}F(q^2)\tilde{a}^i, \quad i = l(\mathrm{e},\mu),\pi, \tag{13}$$

$$\tilde{a}^l = \frac{4q}{\sqrt{4m_l^2+q^2}}\tilde{L}_l + 1 - \frac{4m_l^2}{q\sqrt{4m_l^2+q^2}}\tilde{L}_l,$$

$$\tilde{a}^\pi = \frac{1}{2}\left(\frac{2q}{\sqrt{4m_\pi^2+q^2}}\tilde{L}_\pi - 1 + \frac{4m_\pi^2}{q\sqrt{4m_\pi^2+q^2}}\tilde{L}_\pi\right),$$

$$\tilde{L}_i = \ln\left(\frac{q+\sqrt{4m_i^2+q^2}}{2m_i}\right).$$

For the numerical calculation, we used the dipole approximation [4]:

$$F_E = \frac{F_M}{\mu} = \frac{1}{\left(1+q^2[\mathrm{GeV}^2]/0.71^2\right)^2}, \quad F_E = F_1 - F_2\frac{q^2}{4M^2}, \quad F_M = F_1 + F_2.$$

with $\mu = 2,79$ - the anomalous magnetic moment of proton. Function $F(q^2)$ in the dipole approximation has the form

$$F(q^2) = \frac{4M^2 + q^2\mu^2}{(4M^2+q^2)\left[(q^2[\mathrm{GeV}^2]/(0.71)^2)+1\right]^4}.$$

2. Results

One can see that in the inclusive setup of the process of charged-pair production by interaction of a linearly polarized high-energy photon with a proton, the distribution of recoil proton has a rather pronounced azimuthal asymmetry, from 0.02 at the relatively small polar angles θ up to $\Lambda_{tot} \sim 0.05$ at $\theta \sim \pi/2$, as can be seen from Figs. 2 and 3. This asymmetry increases in an exclusive setup for the processes with heavier particles than e^+e^-. The azimuthal asymmetry of the recoil proton in

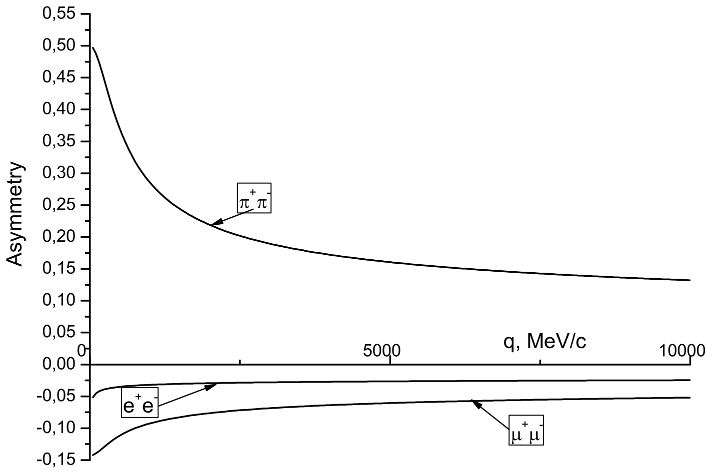

Fig. 2. Asymmetry Λ^i for the cases of e^+e^-, $\mu^+\mu^-$pair and $\pi^+\pi^-$pair production as function of q.

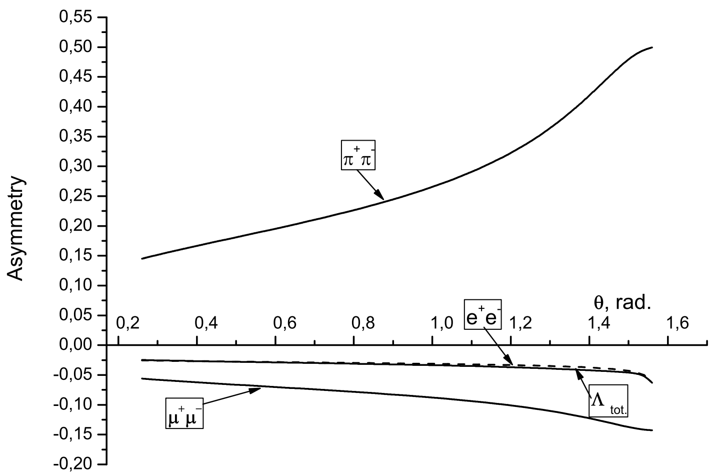

Fig. 3. Asymmetry Λ^i for the cases of e^+e^-pair, $\mu^+\mu^-$pair and $\pi^+\pi^-$pair production and also Λ_{tot} as function of scattering angle θ.

the process of $\pi^+\pi^-$pair photoproduction reaches the value $\Lambda^\pi \sim 0.5$ in the region of small transferred momentum or for polar angles close to the value $\theta \sim \pi/2$. The connection of the process of lepton pair production by exclusive photon–proton scattering with the generalized parton distributions is investigated in Ref. [5]. In Fig. 3 is also depicted the ratio

$$\Lambda_{tot} = \frac{b^{\mathrm{e}} + b^{\mu} + b^{\pi}}{a^{\mathrm{e}} + a^{\mu} + a^{\pi}}$$

which can be considered as the asymmetry averaged over all processes, which estimates the total influence of linear polarization of the initial photon on the value of the azimuthal asymmetry of the recoil proton. For the recoil proton in the inclusive setup, the distribution is the sum over all possible channels, including fermion ($\mathrm{e}^+\mathrm{e}^-$, $\mu^+\mu^-$, $\tau^+\tau^+$) and pseudoscalar meson ($\pi^+\pi^-$, $\mathrm{K}^+\mathrm{K}^-$) pairs. Production of heavy resonances such as $\rho^\pm$ meson can be excluded using experimental cuts.

The photoproduction of an electron–positron pair on an electron in the lowest-order of PT was considered in Ref. [6]. The radiative corrections to the cross section were considered in Ref. [7], and in all orders of PT in the parameter $Z\alpha$ in Ref. [8] – both for the unpolarized case. It turns out that for $Z < 6$, our results can be applied to the photoproduction on nuclei with a relevant modification of $F(q^2)$. The radiative corrections can change the values of a^i and b^i/a^i in the range of $1-2\%$.

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CHARGED PAIR PRODUCTION BY PHOTON SCATTERING ON A PROTON

Istražujemo tvorbu parova nabijenih leptona i pseudoskalarnih mezona u raspršenju foton – proton na visokoj energiji u približenju točkastih čestica. Izračunali smo raspodjele odbijenih protona u inkluzivnim mjerenjima po azimutu i polarnom kutu. Asimetrija $\Lambda_{\rm tot}$ ima vrijednosti od 0.02 za male polarne kutove θ, do 0.05 za $\theta \sim \pi/2$.