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MANIFESTATION OF AN EXCITED ELECTRON IN $e^+e^- \to \gamma\gamma$ REACTION

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The differential cross section and some polarization observables have been calculated for the $e^+e^- \to \gamma\gamma$ reaction taking into account the contribution of the excited electron. The spin correlation coefficients were calculated for the case when both beams are polarized. We consider two approaches for the excited electron contribution: the $ee\gamma\gamma$ contact interaction and the exchange of the excited electron in *t*- and *u*-channels. Numerical estimations are given for the excited electron contribution to the differential cross section and spin correlation coefficients for various values of the electron beam energy and excited electron mass.

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INTRODUCTION

The Standard Model (SM) passed successfully test in precision experiments. In spite of this huge success, there are other issues like the replication of the fermion families, dark matter, baryogenesis etc. that are still not understood within the framework of the SM and addressing them needs physics beyond the SM. Some possible candidate is the compositeness for quarks and leptons [1]. The existence of the excited states is the natural consequence of the composite models of quarks and leptons. The increase of the number of quarks and leptons is often considered as the hint that these particles have substructure. The most convincing proof that quarks and leptons have substructure would be the discovery of the excited states of ordinary quarks and leptons.

At present, there is no completely predictable model describing the substructure of the quarks and leptons. Therefore, the best thing, that can be done for the search of the substructure effects, is to perform the necessary phenomenological analysis. The review of possible effects of the substructure of the quarks and leptons, which can be displayed in various reactions, is given in Ref. [2].

Even though there is no evidence for the excited leptons in the experimental studies performed in HERA, Tevatron, ATLAS and center of mass system (CMS) (see the references in [3]), the colliders with higher center-of-mass energy and luminosity, planned to be installed in the future, will continue to search for their discovery. A possible discovery of the any excited fermion will be a direct proof of the lepton and quark compositeness. The most recent experimental results on the excited electron mass are provided by the OPAL and the ATLAS collaborations [4]. Under some assumption, the mass exclusion limits of the excited electrons are $m_{e^*} > 103.2$ GeV for pair production ($e^+e^- \to e^{*+}e^{*-}$) and $m_{e^*} > 3000$ GeV for single production ($ep \to e^*X \to e\gamma X$).

In this paper we investigate the influence of the $ee\gamma\gamma$ contact interaction on the angular distribution in the reaction of the two-photon annihilation of e^+e^--pair:

$$e^+(p_2) + e^-(p_1) \to \gamma(k_1) + \gamma(k_2). \qquad (1)$$

It was taken into account not only the contribution of the interference of this contact interaction with standard QED mechanism but also the contribution of the contact interaction itself. The influence of the contact interaction on the polarization observables in this reaction has been investigated for the case of both polarized beams. The excited electron can also contribute to the reaction (1) by its exchange in *t*- and *u*-channels. The effect of the excited electron contribution can be seen as distortion in the angular distribution beyond the region of the forward or backward scattering. We investigate also the influence of the excited electron on the polarization observables for the case of both polarized beams.

1. MECHANISM OF EXCITED ELECTRON EXCHANGE

The standard QED mechanism of the reaction (1) is described by two Feynman diagrams. The production of the excited electron in the intermediate state (in *t*- and *u*-channels) in this reaction is described by two additional Feynman diagrams.

The differential cross section of the reaction (1) can be written as follows (the average over the polarizations of the initial beams was done)

$$\frac{d\sigma}{d\Omega} = \frac{\omega}{W}\frac{|M|^2}{128\pi^2}[s(s-4m^2)]^{-\frac{1}{2}}, \qquad (2)$$

where ω is the photon energy in the CMS of the reaction (1), W is the total energy of the initial beams, m is the electron mass, $s = W^2$. The matrix element of the reaction (1) is the sum of two contributions, namely: M_γ (this part corresponds to the pure QED mechanism) and M_{ex} which corresponds to the excited electron contribution.

Then the differential cross section of the reaction (1) can be written, in this approach, as

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_\gamma}{d\Omega} + \frac{d\sigma_{int}}{d\Omega} + \frac{d\sigma_{ex}}{d\Omega}, \qquad (3)$$

where the first term is the cross section of this reaction corresponding to the QED mechanism, the second one – contribution of the interference of two mechanisms (QED and the excited electron) and the last term – the contribution of the excited electron itself.

The matrix element M_γ can be written as

$$M_\gamma = e^2\overline{u}(-p_2)[\frac{\hat{A}_2(\hat{p}_1-\hat{k}_1+m)\hat{A}_1}{(t-m^2)}+ \\ +\frac{\hat{A}_1(\hat{p}_1-\hat{k}_2+m)\hat{A}_2}{(u-m^2)}]u(p_1), \qquad (4)$$

where e is the electron charge; $A_{1\mu}(A_{2\mu})$ is the polarization 4-vector of the first (second) photon; $p_1(p_2), k_1(k_2)$ is the 4-momentum of the electron (positron), first (second) photon, respectively; $t=(p_1-k_1)^2, u=(p_1-k_2)^2$.

At large energies (where at last time the experiments, investigating this reaction, were done) it is possible to neglect by the electron mass m (where it is possible) and then the differential cross section of the reaction (1), caused by the standard QED mechanism (3), has the form

$$\frac{d\sigma_\gamma}{d\Omega}=\frac{\alpha^2}{s}\frac{1+x^2}{1-x^2}, \qquad (5)$$

where $x=cos\theta, \theta$ is the angle between the electron and photon momenta. The coordinate frame in CMS of the reaction (1) is chosen as: z axis is directed along the initial electron momentum and photon momentum lies in the xz plane (the reaction plane). The expression (5) is valid for all angles except forward and backward scattering (i.e., θ = 0, 180°), where it is necessary to take into account the electron mass in the denominator.

We assume that the spin of the excited electron is 1/2 and its interaction with the electromagnetic field is described by following effective Lagrangian [5]

$$L(ee^*\gamma)=\frac{e\lambda}{2M}\overline{u}_e\sigma_{\mu\nu}u_{e^*}F_{\mu\nu}+h.c., \qquad (6)$$

where $\sigma_{\mu\nu}=(\gamma_\mu\gamma_\nu-\gamma_\nu\gamma_\mu)/2$, M is the excited electron mass, λ is the dimensionless coupling constant and $F_{\mu\nu}$ is the photon field-strength tensor. Then the part of the matrix element, describing the contribution of the excited electron to the reaction (1), can be written as

$$M_{ex}=-(\frac{e\lambda}{M})^2\overline{u}(-p_2)[\frac{\hat{A}_2\hat{k}_2(\hat{p}_1+M)\hat{A}_1\hat{k}_1}{(t-M^2)}+ \\ +\frac{\hat{A}_1\hat{k}_1(\hat{p}_1+M)\hat{k}_2\hat{A}_2}{(u-M^2)}]u(p_1). \qquad (7)$$

As it was already mentioned above, at high energies one can neglect the electron mass (we assume also that $M >> m$ and experimental data suggest this assumption). Using expression (7) as matrix element M_{ex} and expression (4) for the matrix element M_γ one can obtain the following formula for the interference contribution (in this approximation)

$$\frac{d\sigma_{int}}{d\Omega}=\frac{\alpha^2\lambda^2}{M^2}[1-x^2+y(1+x^2)][(1+y)^2-x^2]^{-1}, \quad (8)$$

where $y=2M^2/s$. In the same approximation the term, caused by the contribution of the excited electron itself, has the form

$$\frac{d\sigma_{ex}}{d\Omega}=\frac{\alpha^2\lambda^4}{8}\frac{ys^2}{M^6}[4y^3+y^2(1-x^2)(9+x^2)+ \\ 6y(1-x^2)^2+(1-x^2)^3][(1+y)^2-x^2]^{-2}. \qquad (9)$$

The following ratio will be used for the estimation of the excited electron contribution to the differential cross section

$$R_{ex}=(\frac{d\sigma_{int}}{d\Omega}+\frac{d\sigma_{ex}}{d\Omega})/\frac{d\sigma_\gamma}{d\Omega}. \qquad (10)$$

Let us consider the influence of the excited electron on the polarization observables of the reaction (1) for the case when both beams have arbitrary polarization. The mechanism, caused by the exchange of the excited electron, does not lead to a non-zero polarization effects in the case when only one beam is polarized (at least, in the lowest order of the perturbation theory) since the reaction of the excited electron production conserve the space parity (it is seen from the expression for the Lagrangian (6)).

In the case when the initial beams have arbitrary polarizations, the differential cross section of the reaction (1) can be written as

$$\frac{d\sigma}{d\Omega}=\frac{d\sigma_0}{d\Omega}(1+C_{zz}\xi_{1z}\xi_{2z}+C_{xx}\xi_{1x}\xi_{2x}+C_{yy}\xi_{1y}\xi_{2y}+ \\ C_{zx}\xi_{1z}\xi_{2x}+C_{xz}\xi_{1x}\xi_{2z}), \qquad (11)$$

where C_{ij} are the spin correlation coefficients, $\vec{\xi}_1(\vec{\xi}_2)$ is the unit vector along the electron (positron) polarization in its rest system. Thus, ξ_{iz} describes the longitudinal polarization of the beams, and $\xi_{ix}(\xi_{iy})$ – the transverse polarization of the beams and polarization vector lies in the reaction plane (orthogonal to the plane). Let us note that C_{xz}, C_{zx} coefficients are proportional to the electron mass and, therefore, they are zero in the high energy limit. The rest coefficients in this limit have the form

$$\sigma_0 C_{xx}=\frac{\alpha^2}{s}\{1+\frac{\lambda^2 s}{M^2}(1+y)(1-x^2)[(1+y)^2-x^2]^{-1}+ \\ +\frac{\lambda^4}{y^2}(1-x^2)^2[(1+y)^2-x^2]^{-2}\}, \\ C_{yy}=-C_{xx}, \qquad (12) \\ \sigma_0 C_{zz}=\frac{\alpha^2}{s}\{(1+x^2)(1-x^2)^{-1}+ \\ +\frac{2\lambda^2}{y}[1-x^2+y(1+x^2)][(1+y)^2-x^2]^{-1}+ \\ +\frac{\lambda^4}{y^2}[-4y^3+y^2(1-x^2)(x^2-7)-2y(1-x^2)^2 \\ +(1-x^2)^3][(1+y)^2-x^2]^{-2}\},$$

where $\sigma_0=d\sigma_0/d\Omega$ is the differential cross section of the reaction (1) for the case when all particles are unpolarized.

Let us do numerical estimations for the contribution of the excited electron to the observables of the reaction (1). We investigate the dependence of the effect, caused by the contribution of the excited electron, on the excited electron mass M (we use M=150 and 300 GeV), on the total energy of the beams (W=200 and 500 GeV) and on the coupling constant value (λ =1 and 0.1). The influence of these parameters on the ratio R_{ex} is given in Fig. 1.

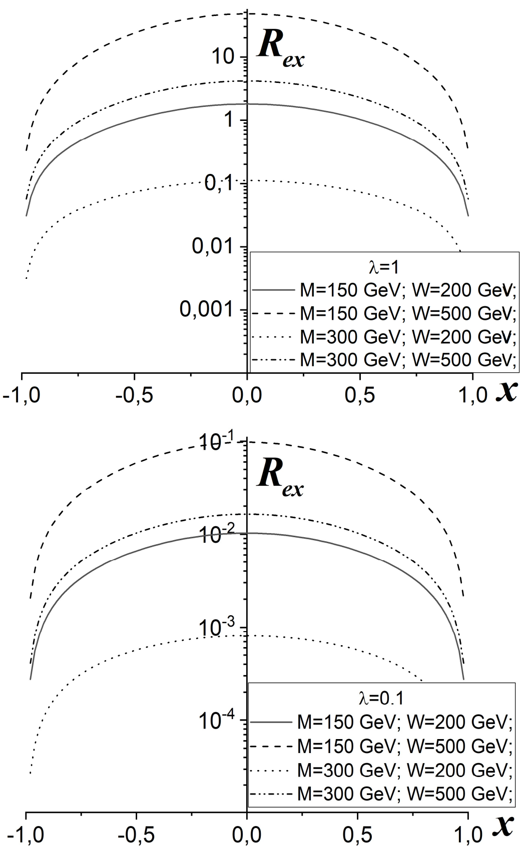

Fig. 1. The ratio R_{ex} for various values of the excited electron mass M, the total energy of the beams W and the coupling constant λ =1 (up) and λ =0.1 (down)

We see that at fixed beam energy the most sensitivity to the contribution of the excited electron takes place at the angles far from the region of the forward scattering since the cross section, caused by the pure QED mechanism, has sharp peak at forward scattering. Note that in this angular region, where the sensitivity to the contribution of the excited electron is maximal, the cross section decreases appreciably and it requires more time to collect comparable statistics. It turns out that at fixed beam energy the excited electron contribution to the ratio R_{ex} decreases strongly with the increase of the mass M. The increase of the beam energy at the fixed mass M leads to the appreciable increase of the excited electron contribution. The sensitivity of the excited electron contribution to the coupling constant λ (at fixed values of M and W) is very strong. For example, if we reduce the λ to one-tenth (from 1 to 0.1) the ratio R_{ex} reduces by a factor of 100. Thus, the investigation of the reaction (1), at future high energy linear electron-positron colliders (CLIC or ILC with W ~ 500 GeV), can give more strict constraints on the excited electron parameters (mass and coupling constant).

We did the numerical estimations of the spin correlation coefficients C_{xx} and C_{zz}. They are given in Fig. 2. The analysis of their behaviour depending on the excited electron mass, the total energy of the beams was done in the same way as for the ratio R_{ex}. One can see from Fig. 2 that the spin correlation coefficients have appreciable values over a wide range of the scattering angles (especially for the C_{zz} quantity).

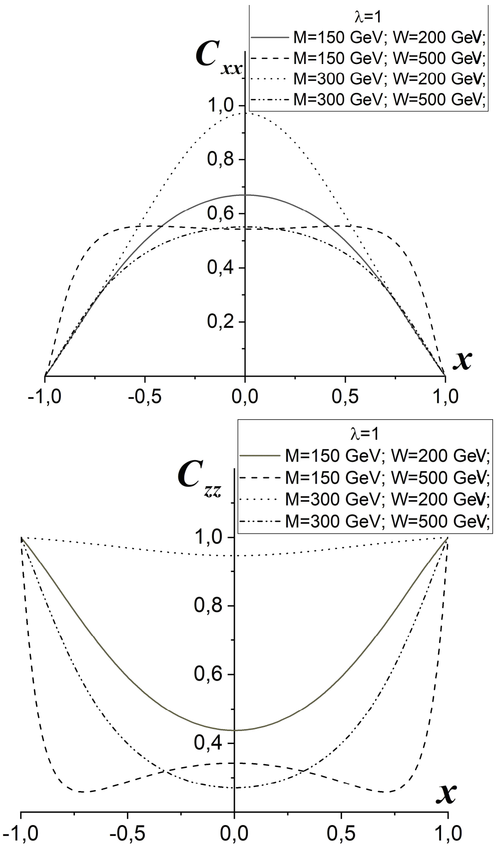

Fig. 2. The spin correlation coefficients for various values of the excited electron mass M, the total energy of the beams W

Note that the coefficient $C_{zz} = 1$ for the pure QED mechanism. Such behaviour of the spin correlation coefficients is important since at small angles the cross section is large and this circumstance permits to collect more data. The spin correlation coefficients do not change strongly with increasing of the total energy W. The dependence of these coefficients on the excited electron mass reduces with the increase of the energy W.

Note that the proposed future linear colliders ILC and CLIC cover, at first run, the region W~ 500 GeV (with longitudinal beam polarization). Both colliders have posible upgrades to 1 (ILC) and 3 TeV (CLIC) [6].

2. CONTACT $ee\gamma\gamma$ INTERACTION

Earlier, the contact $ee\gamma\gamma$ interaction was investigated in a number papers (see, for example [7, 8]) where the contribution of this contact interaction was taken into account to the reaction (1). Besides, in the paper [8] it was considered the manifestation of this contact interaction in the reactions $e^+e^- \to 3\gamma$, $\gamma + F \to F + l\bar{l}$ (where F designates arbitrary fermion). In these papers the contribution of contact interaction was taken into account on the level of its interference with standard QED mechanism. The influence of the initial particle polarizations on the observable characteristics of these processes was not investigated in these papers.

The experimental search for various types of the contact interaction are being done at present at the lepton, lepton-hadron and pure hadron colliders. The references on the experimental search for these contact interactions see in the paper [9]. Using the results of various experiments it was obtained the lower limits for the corresponding energy scales Λ.

The matrix element of the reaction (1) is the sum of M_γ (the pure QED mechanism) and M_{ci} which describes the contribution of the contact $ee\gamma\gamma$ interaction. Then the differential cross section of the reaction can be written, in this approach, as a sum of three contributions, namely, by Eq. (3), where instead of ex index it is necessary to put ci index (the contact interaction contribution). Then, in this case, the second term describes the contribution of the interference of two mechanisms (QED and the contact interaction), and the last one – the contribution to the cross section of the contact interaction itself.

The effective Lagrangian of any contact interaction is constructed using the fields of particles known at present and is proportional to the lowest possible power of $1/\Lambda$ which depends on the dimensionality of the fields entering the Lagrangian. When constructing this Lagrangian, we demand that fermion currents corresponding this Lagrangian conserve the helicity. This assumption is necessary, for example, for various types of the composite models. This condition ensures that masses of known particles are much less than the energy scale Λ.

The contact interaction for two fermions and two bosons was considered, in general case, in the paper [10]. For the case of the $ee\gamma\gamma$, the Lagrangian of the contact interaction can be written as

$$L(ee\gamma\gamma) = 2\frac{ie^2}{\Lambda^4}F_{\mu\sigma}F_{\nu\sigma}\lambda\bar{\psi}\gamma_\mu\partial_\nu\psi + h.c., \quad (13)$$

where ∂_ν is the derivative, ψ is the electron wave function, $F_{\mu\nu}$ is the strength of the electromagnetic field. The dimensions of the fields participating in the effective Lagrangian (12) lead to the fact that it is proportional to Λ^{-4}. The dimensionless coefficient λ determines the strength of the interaction. The transition amplitude corresponding to the contact interaction is real value and can be both positive and negative (and each sign of the parameter λ is associated with different value of the energy scale Λ).

The matrix element M_{ci}, corresponding to the effective Lagrangian (12), can be written in the following general form (in the impulse representation)

$$M_{CI} = -2\lambda\frac{e^2}{\Lambda^4}V_\mu\bar{v}(p_2)\gamma_\mu u(p_1), \quad (14)$$

where

$$V_\mu = [(k_1\cdot k_2 p_1\cdot A_2 - p_1\cdot k_2 k_1\cdot A_2)A_{1\mu} + k_{1\mu}(p_1\cdot k_2 A_1\cdot A_2 - k_2\cdot A_1 p_1\cdot A_2)] + 1\leftrightarrow 2. \quad (15)$$

For the interference contribution (between QED and the contact interaction mechanisms) to the differential cross section of the reaction (1) one can obtain the following simple expression valid at high energies

$$\frac{d\sigma_{int}}{d\Omega} = \lambda\frac{\alpha^2 s}{2\Lambda^4}(1+x^2). \quad (16)$$

In the same approximation ($m=0$), the term corresponding to the contact interaction mechanism itself has the form

$$\frac{d\sigma_{CI}}{d\Omega} = \lambda^2\frac{\alpha^2 s^3}{16\Lambda^8}(1-x^4). \quad (17)$$

Let us consider the influence of the contact interaction on the polarization observables in the reaction (1) for the case when initial particles are polarized. Since in our case the contact interaction does not violate the space parity then non-zero observables arise in the case when only both beams are polarized. The pure QED mechanism of this reaction (at least without taking into account the radiative corrections) does not lead to the polarization effects when only one beam is polarized. The electroweak corrections (at one-loop level) can lead to additional term in the amplitude of this process which violate the parity and, therefore, can lead to the non-zero polarization observables.

Let us consider the case when both beams have arbitrary polarization. Note that synchrotron radiation in the electron-positron colliders leads to the polarization of these beams. This polarization is transverse and its value is appreciable.

The pure QED mechanism lead to the following contribution to the differential cross section of the reaction (1) which depends on the polarization of both beams (in the high energy limit)

$$\frac{d\sigma_\gamma(\xi_1,\xi_2)}{d\Omega} = \frac{d\sigma_\gamma}{d\Omega}[1+\xi_{1z}\xi_{2z} + \frac{1-x^2}{1+x^2}(\xi_{1x}\xi_{2x} - \xi_{1y}\xi_{2y})]. \quad (18)$$

The interference (between QED and the contact interaction mechanisms) contribution to the differential cross section of the reaction (1) caused by the polarization of both beams has the following form (in the high energy limit)

$$\frac{d\sigma_{int}(\xi_1,\xi_2)}{d\Omega} = \lambda\frac{\alpha^2 s}{2\Lambda^4}[(1-x^2)(\xi_{1x}\xi_{2x} - \xi_{1y}\xi_{2y}) + (1+x^2)\xi_{1z}\xi_{2z}]. \quad (19)$$

The term in the differential cross section of the reaction (1), caused by the contribution of the contact interaction itself and depending on the polarization of both beams, has the following form (in the high energy limit)

$$\frac{d\sigma_{CI}(\xi_1,\xi_2)}{d\Omega} = \lambda^2\frac{\alpha^2 s^3}{16\Lambda^8}[(1-x^2)^2(\xi_{1x}\xi_{2x} - \xi_{1y}\xi_{2y}) + (1+x^4)\xi_{1z}\xi_{2z}]. \quad (20)$$

CONCLUSIONS

We have analyzed the influence of a particular mechanism (the excited electron contribution), which is beyond the SM framework, on the observables of the reaction $e^+e^-\to\gamma\gamma$. Two approaches of taking into account the excited electron contribution has been considered: the contact $ee\gamma\gamma$ interaction mechanism and the presence of the excited electron in the t- and u-channels. The influence of these mechanisms on the angular dependence of the differential cross section and spin correlation coefficients (when both initial beams are arbitrarily polarized) have been investigated for the reaction $e^+e^- \to \gamma\gamma$. These effects turned out to be appreciable and their magnitude increases quickly when initial beam energy grows. Therefore, the experimental investigation of this reaction on the future lepton colliders may essentially progress to limit the parameters of the mechanisms under consideration.

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ПРОЯВЛЕНИЕ ВОЗБУЖДЁННОГО ЭЛЕКТРОНА В РЕАКЦИИ $e^+e^- \to \gamma\gamma$

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Дифференциальное сечение и некоторые поляризационные наблюдаемые вычислены для реакции $e^+e^- \to \gamma\gamma$ с учетом вклада возбужденного электрона. Коэффициенты спиновой корреляции были получены для случая, когда оба пучка поляризованы. Было рассмотрено два подхода для учета вклада возбуждённого электрона: $ee\gamma\gamma$ контактное взаимодействие и обмен возбужденным электроном в *t*- и *u*-каналах. Численные оценки для вклада возбужденного электрона в величину дифференциального сечения и коэффициентов спиновой корреляции приведены для некоторых величин энергии электронного пучка и массы возбужденного электрона.

ПРОЯВ ЗБУДЖЕНОГО ЕЛЕКТРОНА В РЕАКЦІЇ $e^+e^- \to \gamma\gamma$

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Диференціальний переріз та деякі поляризаційні спостережувані обчислені для реакції $e^+e^- \to \gamma\gamma$ з врахуванням внеску збудженого електрона. Коефіцієнти спінової кореляції були отримані для випадку, коли обидва пучки поляризовані. Було розглянуто два підходи для врахування внеску збудженого електрона: $ee\gamma\gamma$ контактна взаємодія та обмін збудженим електроном у *t*- і *u*-каналах. Числові оцінки для внеску збудженого електрона у величину диференціального перерізу та коефіцієнтів спінової кореляції приведені для деяких величин енергії електронного пучка та маси збудженого електрона.