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Anti-Chudakov effect in high-energy electron–positron pair ionization loss in thin target

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ABSTRACT

The problem of electron–positron pair ionization loss on different distances from its creation point in substance is considered. It is shown that together with the Chudakov effect of pair loss reduction the opposite effect of exceeding by the pair loss of the doubled value of single electron (positron) loss may take place. It is demonstrated that for pair ionization loss in the same substance where the pair is created such effect is rather small but can enhance by the order of magnitude if consider the pair loss in thin plate situated in the direction of pair motion on some distance from this substance. It is pointed out that such effect should be most significant at relatively low pair energies of several hundreds MeV.

1. Introduction

During the motion of electron–positron pair through substance it looses part of its energy on excitation and ionization of the atoms of the substance. This part constitutes the pair ionization loss. In the vicinity of the pair creation point in substance its value may be smaller than the sum of ionization losses of electron and positron which move through substance separately from each other [1–3]. Such effect, known as the Chudakov effect, was observed in the experiments [4–6] in which ionization losses of the pairs created in emulsions during the traversal of cosmic-ray photons through them were investigated as well as in the experiment [7,8] in which the photons, which generated electron–positron pairs, were created in accelerator and the pairs ionization losses were measured in thin silicon detectors. In papers [9,10] it was theoretically shown that the analogous effect takes place also for total energy loss of the pair in substance (if not take into account loss on bremsstrahlung production) which along with ionization loss also includes loss on the Cherenkov radiation.

The decrease of pair ionization loss in the vicinity of its creation point is caused by destructive interference of the electron's and the positron's fields which leads to their significant weakening on large distances from the pair. Due to the fact that at sufficiently high energies polarization of substance leads to screening of the particles' electric fields on distances from their trajectories $\rho \geqslant 1/\omega_p$ (where ω_p is the plasma frequency of the substance) and the pair divergence angle $\vartheta \sim m/\varepsilon$ is very small (where m is the electron mass and ε is the pair energy) significant suppression of the pair energy loss due to mutual 'extinction' of particles' fields should take place on distances from the pair creation point $z \ll z_0$, where $z_0 = \varepsilon/m\omega_p$. Let us note that in the papers [1–3,9,10] the pair energy loss was considered in the same substance (infinite and homogeneous) in which the pair was created.

In the present Letter we show that together with the Chudakov effect of electron–positron pair ionization loss suppression in the vicinity of its creation point the opposite effect (anti-Chudakov effect) may take place, which means that the magnitude of the pair ionization loss may exceed the sum of the losses of electron and positron (which is the doubled value of a single particle loss) which move in the substance separately from each other. The possibility of such effect is stipulated by the fact that in the region between the electron and the positron their electric fields have the same direction (see Fig. 1) and hence this region should lead to the increase of ionization energy loss. On small distances from the pair creation point ($z \ll \gamma/\omega_p$), however, the contribution of the pair interaction with the atoms of the substance in this region to ionization loss is insignificant and the Chudakov effect of the pair ionization loss reduction takes place (these are the distances for which the consideration of this process in the papers [1–3] is valid). We show that with the increase of z the contribution of the considered region to the pair ionization loss increases and for $z \sim \gamma/\omega_p$ it may exceed the contribution of the region in which the interference of the electron's and the positron's fields

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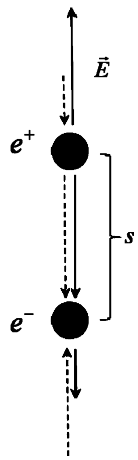

Fig. 1. Electric field of electron–positron pair. Solid arrows – positron's field, dashed arrows – electron's field.

is destructive. In homogeneous infinite substance, however, such effect is rather small.

However, as we show, the considered effect of exceeding by the pair ionization loss of the doubled value of a single electron (positron) loss may enhance by an order of magnitude, if consider the pair ionization loss not in the same substance in which it is created but in thin plate situated in vacuum in the direction of the pair motion on some distance from this substance. The attention here is paid to the fact that in such situation the considered effect is most significant at sufficiently low energies of the pair of the order of several hundreds MeV.

2. The case of homogeneous infinite medium

Firstly, let us consider the ionization loss of ultra relativistic electron–positron pair in the vicinity of its creation point in homogeneous infinite substance. In the paper [11] the expression for its value applicable on arbitrary distances from the pair creation point was obtained. In this paper, however, the major attention was paid to investigation of the pair ionization loss under conditions which correspond to experiment [7,8], when the pair energy loss is significantly suppressed. In the present paper we will consider the pair energy loss in the region of distances from its creation point in which significant contribution to ionization loss is made by collisions with the atoms of the substance in the region of space around the pair where the interference of the electron's and the positron's fields is constructive.

According to [11], the expression for ultra relativistic pair ionization loss in homogeneous infinite medium on distance z from its creation point has the following form:

$$\frac{d\boldsymbol{\varepsilon}}{dz} = 2\omega_p^2 e^2 \left\{ \ln\frac{q_0}{\omega_p} - \frac{1}{2} - K_0(\lambda) + \frac{\lambda}{2} K_1(\lambda) \right\}, \tag{1}$$

where $\lambda = 2\omega_p z/\gamma$. The value of λ in the expression (1) corresponds to the most probable angle of the pair divergence $\vartheta = 2/\gamma$ [12], where γ is the Lorentz factor of a single particle of the pair (we assume that the energy of the pair is uniformly spread between the electron and the positron).

Formula (1) is obtained on the basis of method in which substance is considered in Fermi model as a set of oscillators which represent bound electrons in atoms and the total energy transfer to a single atomic electron (oscillator) by the field of electron–positron pair is defined by the square of module of the Fourier component $\vec{E}_{\omega_0}$ of this field at frequency equal to the oscillator's own frequency ω_0 [13]. The own frequencies ω_0 of the considered oscillators have been chosen to equal the mean ionization potential I of the atoms of the substance. The quantity q_0^{-1} in the expression (1) is the minimum value of the impact parameters for which such model is applicable. By the order of magnitude q_0^{-1} coincides with characteristic interatomic distance of the substance. Taking into account that the pair divergence angle is rather small it was assumed that the field created by the pair in substance at the moment of time at which the electron and the positron are on distance s from each other (Fig. 1) coincides with the field created by these particles in the situation when they are separated by the same distance but move with parallel velocities.

The first two items in braces in (1) correspond to the doubled value of ionization loss of a single electron (or positron) which moves in the substance. In the region of distances $z < \gamma/\omega_p$ according to (1) the pair ionization loss is less than this value and the Chudakov effect takes place. In the region $z \sim \gamma/\omega_p$ the expression (1), on the contrary, exceeds this value but the relative excess by the pair ionization loss in this region of its value on large distance $z \to \infty$ from the pair creation point $\delta\boldsymbol{\varepsilon} = \lfloor (d\boldsymbol{\varepsilon}/dz)_{z\sim\gamma/\omega_p} - (d\boldsymbol{\varepsilon}/dz)_{z\to\infty} \rfloor / (d\boldsymbol{\varepsilon}/dz)_{z\to\infty}$ is rather small. In particular for $z = \gamma/\omega_p$ it is equal to several tenths of a percent.

As was noted above, in the papers [1–3] only the effect of decrease of pair ionization loss due to destructive interference of the electron's and the positron's fields is discussed. In [1,2] this is due to the fact that the range of applicability of theories proposed here are restricted by the distances from the pair creation point $z < \gamma/\omega_p$ (in particular in [1] $z < 0.6\gamma/\omega_p$) which is caused by the absence of consecutive consideration of the effect of the electron's and the positron's fields screening in substance during the calculation of the pair ionization loss. In [3] the results of calculation are also presented for the case $z \ll z_0$.

3. The case of a thin plate

In the paper [11] a somewhat different statement of the problem about ionization loss of electron–positron pair was also considered. The energy loss of ultra relativistic pair was calculated here in thin plate situated in vacuum in the direction of the pair motion on different distances from the substance in which the pair had been created. The interface between this substance and vacuum was assumed to be flat. Such problem statement is similar to the one which was used in the experiment [9]. Let us show that in this situation the effect of exceeding by the pair ionization loss of the doubled value of single electron (positron) loss enhances by an order of magnitude in comparison to the case when the pair moves in homogeneous infinite substance. The thickness of the plate δz in this case should be less than the characteristic length of absorption of photons in it of frequencies which make the main contribution to ionization. This can be expressed by the condition $\delta z \ll I/\eta_p^2$ [14,15] in which I is the mean ionization potential of the atoms of the plate, η_p is its plasma frequency.

The expression for ionization loss of the pair per unit path in the plate situated on distance z_1 from the substance has the following form [11]:

$$\frac{d\boldsymbol{\varepsilon}}{dz} = 2\eta_p^2 e^2 \int dq\, q^3 \left\{ Q_c^2 + Q_f^2 + 2Q_f Q_c \cos\left(\frac{Iz_1}{2\gamma^2} + \frac{q^2 z_1}{2I} \right) \right\} \times \left[1 - J_0(2qz_1/\gamma) \right], \tag{2}$$

where

$$Q_f(q) = \frac{1}{q^2 + \omega_p^2 + I^2/\gamma^2} - \frac{1}{q^2 + I^2/\gamma^2},$$

$$Q_c(q) = \frac{1}{q^2 + I^2/\gamma^2},$$

ω_p is the plasma frequency of the substance in which the pair is created and $J_0(x)$ is the Bessel function. The value of the pair