38

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ELECTRON-POSITRON PAIR CREATION BY PHOTONS IN AN ALIGNED SINGLE CRYSTAL: COMPARISON OF THEORY WITH EXPERIMENT

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Abstract

The creation of electron-positron pairs by 50-110 GeV photons directed along the ⟨110⟩ axis of a cooled Ge crystal is considered. The results obtained are compared with a very recent experiment performed in CERN. Radiation from electrons is also discussed.

When very energetic electrons or photons are directed along the axes or planes of a single crystal the processes of photon radiation and pair creation are substantially modified. In particular, a photon can create an electron-positron pair not only on the isolated atoms (Bethe-Heitler mechanism), or on the atoms with the periodicity of the lattice potential taken into account (mechanism of coherent pair creation), but also in the field of a single string or plane [1,2]. A theoretical study of the effect was continued in Refs.[3,4]. There is a systematic quantitative discrepance between the results of Refs.[1,3] and ours (Refs.[2,4]). Very recently an experiment has been performed in CERN with participation of the authors of Ref.[1] where the e^+e^- pair creation by 50-110 GeV photons was observed when the incident photon beam was directed along the ⟨110⟩ axis of a cooled Ge crystal (T = 100 K) which was 1.4 mm thick [5] . In this important experiment the enhancement of pair creation by a photon near the axis was observed for the first time. In this letter we report an analysis of this experiment in the framework of our theoretical approach [2,4] .

In Ref.[4] the general expression for the total probability of pair creation by a photon (for the whole time of interaction) was obtained. In our derivation we used only the quasiclassical nature of motion of pair particles and retained the main terms of expansion in m/ω :

$$w_e=\frac{\alpha}{(2\pi)^2}\frac{m^2}{\omega}\int\frac{d^2\rho_0}{S}d^2p_{0\perp}\frac{d\varepsilon}{\varepsilon\varepsilon'}\int dt_1dt_2\left[1-\frac{\varepsilon(\varepsilon^2+\varepsilon'^2)}{4\varepsilon' m^2}\left(\mathbf{v}_\perp(t_1)-\mathbf{v}_\perp(t_2)\right)^2\right]e^{iA}, \quad (1)$$

$$A=\frac{\varepsilon\omega}{2\varepsilon'}\int_{t_1}^{t_2}dt\left[\frac{m^2}{\varepsilon^2}+\left(\mathbf{n}_\perp-\mathbf{v}_\perp(t)\right)^2\right]$$

where m is the electron mass, ω is the photon energy; ε ,

$\varepsilon' = \omega - \varepsilon$ are the energies of the particles of the produced pair, $\mathbf{n} = \mathbf{k}/\omega$, $\mathbf{v}(t)$ is the velocity of one of the produced particles, index $\perp$ denotes the vector component transverse to the z-axis which lies along the string of atoms for the axial case and along the $\mathbf{n}$ component parallel to a plane for the plane case; $\mathbf{p}_{0\perp}$ is the particle momentum at the creation point $\boldsymbol{\varrho}_0 = \mathbf{r}_{0\perp}$. The summation over all the particle trajectories is made by means of the integral $\frac{1}{S}\int d^2\varrho_0 \, d^2 p_{0\perp} \, d\varepsilon$ where S is the transverse area over which the integral is taken. The periodicity of the crystal allows one to use as s the area per one string (plane). Equation (1) is valid for any fields, including the strongly non-uniform ones, and, in particular, for any photon incident angles ϑ_0 (the angle between $\mathbf{k}$ and the z-axis).

It was shown in Refs. [2,4] that for the incident angles $\vartheta_0 \ll \frac{V_0}{m}$ one can use the constant field limit. In Ref. [4] we traced a transition from Eq. (1) to the probability of pair creation (per unit time) W_e in the constant field (Eq. (5) in Ref. 4)). This expression for W_e is valid also in the case when the field in the main contribution region is not axisymmetric. It follows from the calculation that one can use the simplified (near-threshold) Eq. (11) of Ref. [2] under conditions of the experiment [5] with an accuracy better than 20%. We started in our calculation with the Moliere potential for an isolated atom. The string potential (taking into account thermal vibrations) is convenient to present in the form (4) of Ref. [2] (for details see Ref. [6]), where the parameters of the potential for the $\langle 110 \rangle$ axis of a cooled Ge crystal (T = 100 K) are the following: V_0 = 114.5 eV, η = 0.063, x_0 = 19.8; the potential well depth is U_0 = 318 eV. The total probability W_e under conditions of the

experiment [5] is presented in Fig. 1. Figure 2 gives the electron (positron) energy distribution under the same conditions.

For large enough incident angles ϑ_0 the motion of the produced particles will differ only slightly from a rectilinear one. After carrying out the corresponding expansion in Eq. (1), we obtain the transition rate for the coherent pair creation by a photon (see, e.g., [7]). In this case, the expansion parameter is $(V_0/m\vartheta_0)^2$. Thus, the single expression (1) is valid for any incident angles ϑ_0. For the photons of high enough energy (the threshold of the effect is discussed in Ref. [2]) at $\vartheta_0 \ll \frac{V_0}{m}$ this expression describes the pair creation probability in the constant field and gives (in the alternative approximation $\vartheta_0 \gg \frac{V_0}{m}$) the transition rate of coherent pair creation.

In Ref. 5 the value of $R = \frac{W_A - W_{NA}}{W_{NA}}$ is presented and as W_{NA} the authors took the transition rate measured at $\vartheta_0 \approx 3900\ \mu$rad, as it follows from Fig. 3 of Ref. [5]. For this angle we have $V_0/m\vartheta_0 \simeq 0.06$. It is worth stressing that for these angles the coherent pair creation mechanism is dominant. It is necessary to take into account the incoherent Bethe-Heitler contribution. In addition, one should bear in mind that the incoherent Bethe-Heitler contribution is also modified (see, e.g., [7]). Under the experimental conditions [5] we obtained $W_{BH}^{M} \simeq 0.28$ cm^{-1} ($W_{BH} \simeq 0.32$ cm^{-1} in the corresponding amorphous media). The events were selected in the 50-110 GeV photon energy range for the "non-aligned" case in Ref. [5] . We obtained $\langle W_{coh} \rangle = 0.57$ cm^{-1} in this energy range for the mean value of the transition rate of coherent pair creation. Note that for the 80-110 GeV photon energy range the value of $\langle W_{coh} \rangle$ increases only by a few percent. The value of R, presented in Ref. [5] , can be written down, using our notation, as follows:

$$R = \frac{W_e - \langle W_{coh} \rangle}{W_{BH}^{M} + \langle W_{coh} \rangle} \tag{2}$$

Let us remind that W_e is the total probability of pair creation in the constant field calculated using Eq. (5) in Ref. [4]. The value of R is plotted in Fig. 3 where the experimental results of Ref. [5] are given as well. Quite good agreement between theory and experiment can be consiedred as an evidence of that the pair creation in the field of the string is really observed in the experiment [5]. Our theoretical curve in Fig. 3 lies rather lower than the curve "Theory x 1/10" in Ref. [5]. Remind that the theoretical prediction in our paper [2] (for the diamond <110> axis) was 9+5 times lower than in Ref. [1]. The discrepance (somewhat smaller) still exists between our papers [2,4] and Ref. [3]. The discrepance between the theoretical predictions presented in Ref. [5] and the experiment (more than by one order of magnitude) is due to two reasons: 1) in W_{NA} for $\vartheta_0 \approx 3900\,\mu$rad we have to take into account W_{BH}^{M} as well as $\langle W_{coh} \rangle$ and the last contribution is very essential; 2) our theoretical predictions are still several times lower than the theoretical predictions presented in Ref. [5].

Let us discuss the dependence of the pair creation probability on the photon incident angle ϑ_0. It follows from the theory of coherent pair creation that the transition rate W_{coh} is maximum when $\vartheta_0 \sim \vartheta_m \equiv \frac{m^2 \Delta}{\pi \omega}$, where Δ is the typical distance between the axes. We will consider the case when $\frac{\vartheta_m m}{V_0} > 1$. Let us trace the behaviour of W_{coh} if we start with the angles $\vartheta_0 \gg \vartheta_m$ and then shift on the left (ϑ_0 decreasing). In this case, the value of W_{coh} increases, attains a maximum at $\vartheta_0 \sim \vartheta_m$, and then decreases with decreasing ϑ_0. This decreasing of W_{coh} continues until $\vartheta_0 = 0$ if the photon energy is lower than the threshold of pair creation. But if the photon energies are high enough so that the pair creation in the field of string is essential, then at $\vartheta_0 \sim \frac{V_0}{m}$ the transition rate stops decreasing. For smaller ϑ_0 the behaviour of the transition rate is due to the constant field mechanism. The behaviour at $\vartheta_0 \sim \frac{V_0}{m}$ depends on the interrelation between $W_{coh}(\vartheta_m)$ and $W_e(\vartheta_0 \ll \frac{V_0}{m})$. When the photon energy increases, ϑ_m shifts to $\vartheta = V_0/m$ and if $\vartheta_m \simeq \frac{V_0}{m}$ the pair creation probability attains its maximum. In the latter case, the theory of coherent pair creation fails where its probability is maximum.

In Ref. [3] the probability of "the crystal-assisted pair creation" vanishes at the angles of the order of $\vartheta_c \gtrsim \sqrt{\frac{u_0}{\omega}}$. This very narrow angular range over which the effect extends is due to the fact that in Ref. [3] only the bound states of electrons are taken into account. However, at the same time one should take into account also the electrons created in continuous states (above-barrier or quasichanneled electrons) the contribution of these states dominates at the angles $\vartheta_0 \gtrsim \vartheta_c$.

In the experiment [5] $\frac{V_0}{m} \simeq 200\,\mu$rad, $\vartheta_m(\omega = 100$ GeV$) \simeq 10^3\,\mu$rad, and $W_e(\vartheta_0 \ll \frac{V_0}{m}) \sim W_{coh}(\vartheta_m)$. Under these conditions a minimum transition rate is attained at the incident angles $\vartheta_0 \sim \frac{V_a}{m}$ and this minimum cannot be very deep. A sharp reduction of the transition rate of pair creation at $\vartheta_0 \approx 40\,\mu$rad [5] cannot be explained in terms of our theory because we have $W_e(\vartheta_0 = 0) \simeq W_e(\vartheta_0 =$ 40 μrad). For incident angles $\vartheta_0 \simeq 400\,\mu$rad we computed the transition rate using the theory of coherent pair creation. For the photon energy range ω = 80-110 GeV we obtained R = 0.64. This result is in satisfactory agreement with the experiment [5] (one should bear in mind that the angle $\vartheta_0 \approx 400\,\mu$rad lies near the boundary of the range where the coherent creation theory is applicable).

Ref. [5] contains also information about the radiation from the 150 GeV electron beam moving along the $\langle 110 \rangle$ axis of cooled Ge. The radiation at axial channeling of very high energy electrons was discussed in Ref. [8]. If the electrons have an energy of the order of several tens of GeV, then it appears that $\chi(\varrho,\varepsilon) \sim 1$ ($\chi(\varrho,\varepsilon)$ is the parameter which determines the characteristics of the radiation $\chi(\varrho,\varepsilon) = \frac{\varepsilon}{m}\frac{E(\varrho)}{E_0}$ where $E(\varrho)$ is the electric field of the string, $E_0 = m^2/e = 1.6 \cdot 10^{16}$ V/cm; the photons with energies $\omega \sim \varepsilon\chi/(2+5\chi)$ are mainly radiated). When $\chi(\varrho,\varepsilon) \sim 1$ it is necessary to use the quantum radiation theory. In the same energy range the radiation length of channeling radiation L_{ch} $(L_{ch}^{-1} = \frac{1}{\varepsilon}\frac{d\varepsilon}{dl})$ is comparable with the dechanneling length ℓ_d due to multiple scattering. For the $\langle 110 \rangle$ axis in Ge $L_{ch} = \ell_d$ for $\varepsilon \simeq$ 40 GeV when $\chi(a_s,\varepsilon) \simeq 0.25$. For higher energies it is possible not to take into account the multiple scattering on radiation length, and the electron distribution in a phase space is determined mainly by radiation.

For the experiment [5], the radiation length is $L_{ch} = 1$ mm for incident particles. This length is 23 times shorter than the radiation length in the corresponding amorphous media. Because L_{ch} is shorter than the crystal thickness $\ell = 1.4$ mm, it is necessary to solve the relevant kinetic problem. Here we restrict ourselves to a rough estimate of the average energy $\bar{\varepsilon}$ of electrons leaving the crystal: $\bar{\varepsilon}/\varepsilon \lesssim 0.25$.

It follows from the above results that the electrons or photons of very high energy, directed along the axes or planes of a single crystal, will cause a specific electromagnetic shower occurring at much shorter lengths than in the corresponding amorphous media.

It is obvious that alongside with the discussed processes in the field of the strings or planes of a single crystal any other processes known in external field, e.g. pair creation by a charged particle, photon splitting, neutrino pair production ($e \to e\nu\bar{\nu}$), can take place. In an analysis of them the results for external field can be used in the same way, as in Refs. [2,4].

FIGURE CAPTIONS

Fig.1. The probability of pair creation by a photon directed along the $\langle 110 \rangle$ axis of a cooled Ge crystal (T = 100 K). The dashed line is the probability of pair creation in the corresponding amorphous media (Bethe-Heitler mechanism).

Fig.2. Energy spectra of electrons (positrons) for the $\langle 110 \rangle$ axis of Ge (T = 100 K) averaged over incident photon energies ω = 80-110 GeV, $x = \varepsilon / \omega$. Curve a is the energy spectra for amorphous media.

Fig.3. The value of R (Eq.(2)), computational results and experimental data [5] .

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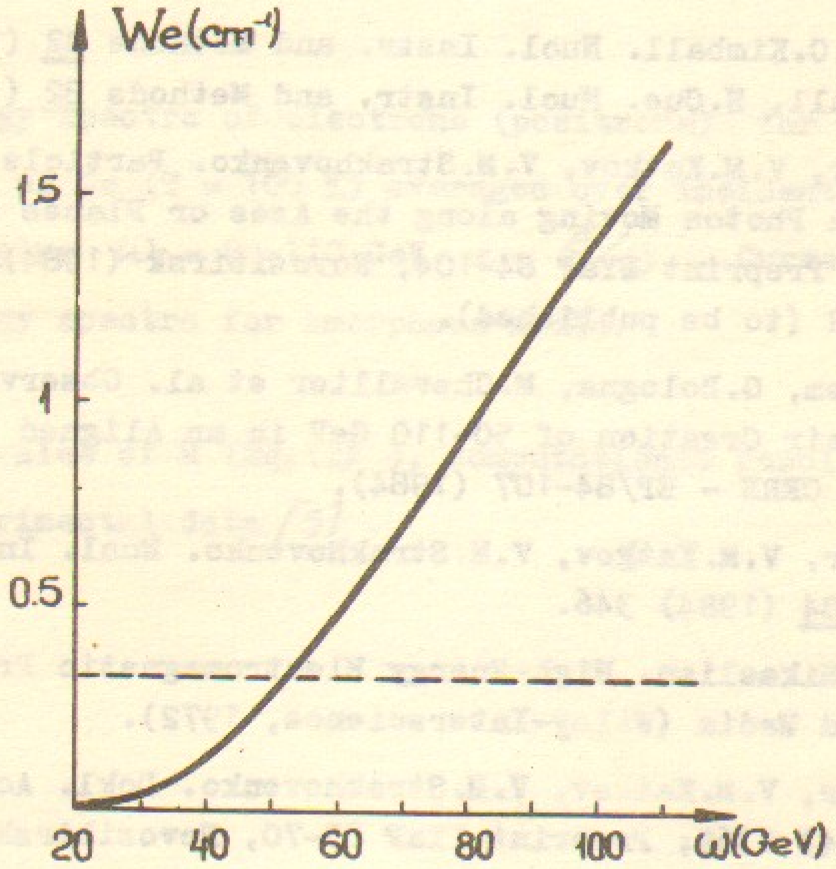

Fig.1

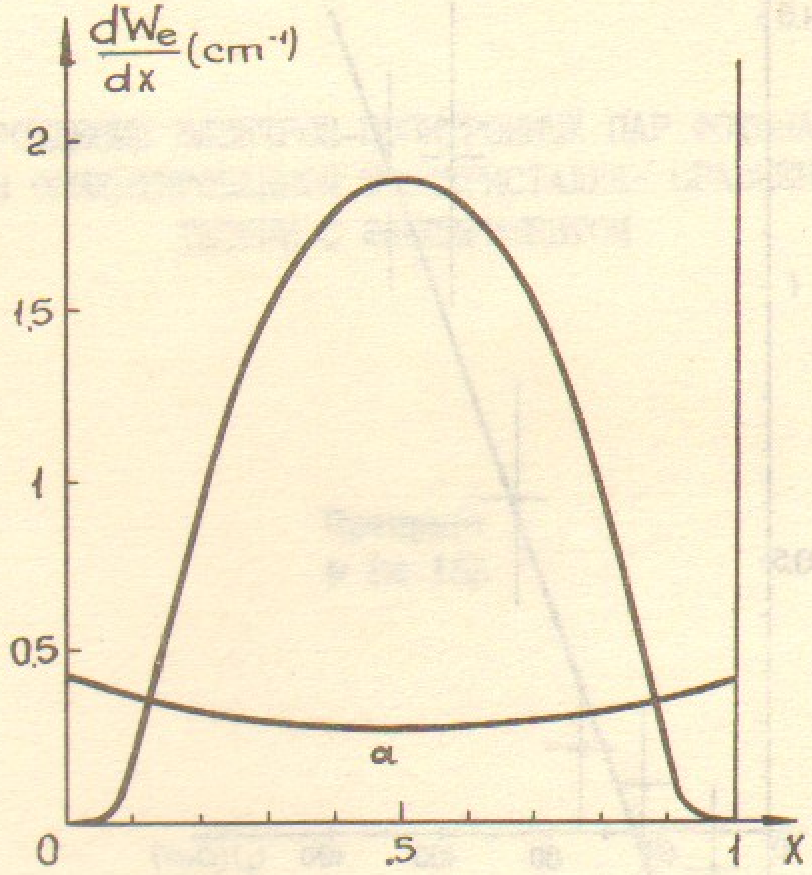

Fig.2

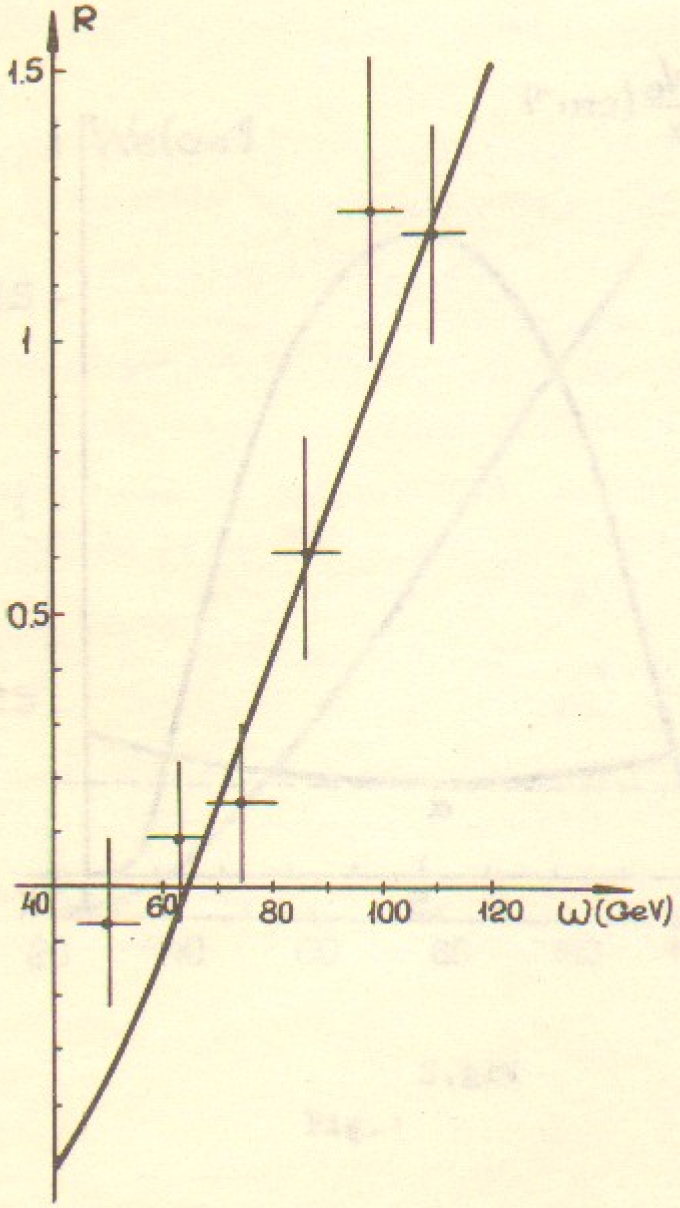

Fig.3

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