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**OBSERVATION OF CHANNELING AND BLOCKING EFFECT
IN PAIR CREATION IN Ge CRYSTAL**

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ABSTRACT

Angular and energy distributions of electrons and positrons created by 83-133 GeV photons in an aligned crystal (strong field pair creation) have been measured. The experiment exhibits the "blocking" effect for the positron and the difference of energy loss between channeled electron and quasi-channeled positron. The data are well reproduced by a Monte-Carlo simulation.

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1. Introduction

Interactions of high energy $e^\pm$ and γ with an oriented crystal allow testing QED in strong field^[1,2]. In this paper we consider pair creation in the quasi-uniform field of an atomic string, which has been observed in previous experiments with photons of energies between 20 and 150 GeV^[3-5]. As we will show below, a peculiarity of pair creation in an aligned crystal is that nearly 100 % of the produced electrons are initially in a channeled state, whereas the corresponding fraction is only of the order of a few percent in the case of an incident electron beam ; therefore the channeling effects already observed with electron beams at 150 GeV^[6-8] (strong radiation, transverse energy cooling^[9-11]) should be strongly enhanced in our situation.

We assume that, in a first approximation (discussed in section 5), the electron and the positron are created at the same point in the crystal and with collinear momenta. However their trajectories are governed by opposite forces $\vec{F}(\vec{r}) = \pm e\vec{\mathcal{E}}(\vec{r})$, where $\vec{\mathcal{E}}(\vec{r})$ is the longitudinally averaged field^[12] at transverse position $\vec{r}$ with respect to the nearest atomic string ("axis"). So the electron is attracted and the positron is repelled by the axis. Since the creation point $\vec{r}_{in}$ is close to the axis (region where the field is maximum), the transverse energy $E_{in,T}^- = \frac{1}{2}E_{in}^- \theta_\gamma^2 - eV(r_{in})$ of the electron is negative, whereas the positron one, $E_{in,T}^+ = \frac{1}{2}E_{in}^+ \theta_\gamma^2 + eV(r_{in})$, is positive (E_{in}^- and E_{in}^+ are the initial energies of the electron and positron and θ_γ is the angle between the photon trajectory and the axis). Accordingly the electron is initially *channeled* whereas the positron is *quasi-channeled*. Therefore we must observe different angular distributions for the electrons and the positrons : the distribution of the emerging positrons will be minimum at $\theta_{out}^+ = 0$ (*blocking effect*), while the distributions of electrons will be maximum at $\theta_{out}^- = 0$ (θ_{out}^- and θ_{out}^+ are the electron and positron exit angles with respect to the axis). Furthermore the electron, which in the average travels in a stronger field than the positron, must radiate more energy than the later by channeling radiation.

The CERN NA46 experiment^[13,14], performed in 1990, was devoted to the search

for a neutral particle produced in a strong field and decaying into an electron-positron pair in the mass range 1-10 MeV. It required a good mass reconstruction and therefore very precise angle and energy measurements. In order to test the self-consistency of the experiment, it was necessary to compare the experimental data with a precise simulation of channeling effects.

As a by-product of this experiment, we can thus exploit the collected experimental data and the analysis methods to study the above mentioned effects. The present paper presents experimental and simulated distributions concerning channeling and blocking.

2. Description of the apparatus

Figure 1 is a sketch of the experimental setup, described in more details in Ref [14]. The photon beam is produced by bremsstrahlung in a 0.1 radiation length lead foil from a high purity 150 GeV electron beam ; the divergence of this beam is $\sigma_{\theta_x}=40 \mu\text{rad}$ in the horizontal plane and $\sigma_{\theta_y}=50 \mu\text{rad}$ in the vertical plane. The trajectories of the electrons are bent by the magnet B1. The photon in the energy range 83-133 GeV is tagged by measuring the final energy of the electron in a four lead-glass detector. The Ge single crystal (0.42 mm thick) is mounted on a two-axis goniometer having an angular resolution of $1.4 \mu\text{rad}$ and cooled to 120 K. Its $\langle 110 \rangle$ axis is aligned with the beam. A microstrip detector (steps of $50 \mu\text{m}$) made of four parallel plates ($20 \times 20 \text{ mm}^2$, thickness 0.3 mm each) is located 78.6 meters beyond the crystal. It determines the x and y positions of the charged particles, relative to the center of the microstrips, and thus the projected $\theta_{out,x}$ and $\theta_{out,y}$ with a resolution $\sigma_{\theta_x} = \sigma_{\theta_y} = 0.2 \mu\text{rad}$. The beam line between the crystal and this detector is kept under vacuum and is shielded against the earth magnetic field by a mu-metal tube. Behind the microstrip detector a spectrometer (consisting of a magnet, B5, and three double MWPC) allows the determination of the positron and electron momenta in the range 11-116 GeV/c with a precision $\sigma_p/p = 0.6\%$ at 50 GeV/c. The association of the tracks before and after the magnet, in the horizontal plane, determines the x positions of the e^- and the e^+ on the microstrip detector. On the contrary, for the y position we

cannot say which one of the two signals belongs to the positron and which one to the electron. To summarize, the angles $\theta_{out,x}^-$, $\theta_{out,x}^+$ and $|\theta_{out,y}^+ - \theta_{out,y}^-|$ are determined.

3. Simulation method

The simulation process comprises two steps. First, we generate an e^+e^- pair inside the channel, then we simulate the histories of the electron and positron in the crystal. For the second step, we use an existing MonteCarlo program^[15,16] which calculates channeled or quasi-channeled electron and positron trajectories at ultrarelativistic energies. This code^[15] has successfully reproduced the energy loss spectra and photon multiplicities of NA33^[7] CERN experiment. It takes into account the most important phenomena of ultrarelativistic $e^\pm$ channeling : Kumakhov radiation, transverse energy damping, multiple scattering and incoherent bremsstrahlung.

For the first step, we take into account two mechanisms : *the strong field pair creation* (SF) and the *incoherent Bethe-Heitler pair creation* (IBH). The incident photon energy E_γ is randomly chosen between $E_{\gamma,min} = 83$ GeV and $E_{\gamma,max} = 133$ GeV according to the approximate $(1/E_\gamma)$ distribution of bremsstrahlung radiation weighted by the total pair creation rate $P_{IBH} + P_{SF}(E_\gamma)$ ($E_{\gamma,min}$ and $E_{\gamma,max}$ are fixed by the energy acceptance of the tagging detector). The proportion of this two processes is given by their respective cross sections for each incident photon energy. The depth at which the pair is created is uniformly sampled between 0 and 420 μm . We neglect the angles between the incident photon and the produced charged particles . The projected photon angles $\theta_{\gamma,x}$ and $\theta_{\gamma,y}$ are randomly chosen according to gaussian distributions of the same widths as those of the electron beam (multiple scattering in the lead foil and non collinearity of bremsstrahlung are neglected). We considered only the case where the crystal is aligned with the photon beam ($\bar{\theta}_{\gamma,x} = 0$, $\bar{\theta}_{\gamma,y} = 0$). The distribution of the transverse position $\vec{r}_{in}$ of the pair in the channel depends on the process and is described below.

For the strong field pair creation, the probability per unit length at a distance r_{in}

from the string is given by^[17]

$$\mathcal{P}_{SF}[\chi(r_{in})] = \frac{\alpha mc}{3\pi\sqrt{3}\gamma\hbar} \int_0^1 \frac{9-u^2}{1-u^2} K_{\frac{2}{3}} \left(\frac{8}{3\chi(1-u^2)} \right) du ,$$

where $\alpha = 1/137$, $\gamma = E_\gamma/mc^2$, mc^2 is the electron mass, $K_{\frac{2}{3}}$ is a Bessel function and $\chi(r) = \gamma\mathcal{E}(r)/\mathcal{E}_{cr}$ is the strong field parameter; $\vec{\mathcal{E}}(\vec{r})$ is the continuous electric field at transverse position $\vec{r}$; $\mathcal{E}_{cr} = m^2 c^3 / e\hbar = 1.32 \times 10^8$ V/Å is the critical field of QED. The photon energy E_γ is shared between electron and positron according to the distribution^[17-20]

$$\frac{d\mathcal{P}_{SF}(\chi, \eta_{in})}{d\eta_{in}} = \frac{\alpha mc}{2\gamma\hbar} \times \left(\int_x^\infty A_i(t) dt - \frac{2}{x} \times \left(\frac{1+\eta_{in}^2}{1-\eta_{in}^2} \right) \times A'_i(x) \right) ,$$

with $\eta_{in} = (E_{in}^+ - E_{in}^-)/(E_{in}^+ + E_{in}^-)$ and $x = [(1-\eta^2)\chi/4]^{-2/3}$; A_i is the Airy function, A'_i its derivative.[†]

In addition to the strong field pair creation we have also the incoherent Bethe-Heitler process on individual nuclei (IBH). In this case $\vec{r}_{in}$ is chosen randomly according to a gaussian distribution of width $\sigma_{x_{in}} = \sigma_{y_{in}} = u_{th} = 0.0542$ Å, where u_{th} is the thermal + quantum vibration amplitude of the lattice at 120 K. For the sake of simplicity we took a flat energy partition between e^+ and e^- in the IBH mechanism.

4. Results

The experimental data which are presented in this paper concern two different sets of events. The first set contains about 40 000 events where one positron and one electron were detected unambiguously in the device microstrip+MWPC ("two-tracks events"). The second set contains about 4000 events with only one hit on the microstrip ("one track event"). Both sets were collected during the same runs, where the crystal was best aligned with the beam. This alignment was performed with the electron beam by removing the lead radiator and looking for the maximum yield of channeling radiation. An alignment sensitivity of 5μrad was obtained.

[†] In Refs 18 and 19, the same formula is written with an extra factor $\pi^{-1/2}$ due to a different normalization of the Airy function.

In Fig. 2-5 we will show experimental and Monte Carlo distributions which are normalized at the same area.

4.1. Two-tracks events. Figure 2 shows the electron (Fig. 2a) and the positron (Fig. 2b) measured angular distributions (dots) projected on the horizontal plane. The simulation results (full line) are also presented. The abscissa is defined by : $\tilde{\theta}_x = x/L$, where x is the horizontal position with respect to the center of the microstrip plane and $L = 78.6$ meters the distance between the crystal and the microstrip detector (similary for $\tilde{\theta}_y = y/L$). $\tilde{\theta}_x$ and $\tilde{\theta}_y$ differ from $\theta_{out,x}$ and $\theta_{out,y}$ by small constants $\tilde{\theta}_{0x}$ and $\tilde{\theta}_{0y}$ due to a slight misalignement between the $< 110 >$ axis and the center of the microstrip detector ($\theta_{out,x} = \tilde{\theta}_x - \tilde{\theta}_{0x}$, $\theta_{out,y} = \tilde{\theta}_y - \tilde{\theta}_{0y}$). The observed angular distribution is smeared relatively to the true one by two effects : first the angular resolution ($\sigma_{\theta_x} = \sigma_{\theta_y} = 0.2 \mu\text{rad}$) of the microstrip, second the transverse size of the beam $\phi = 8\text{mm}$. The later effect yields the main part of the uncertainty $\sigma'_{\theta_x} = \sigma'_{\theta_y} = \phi/4L = 25 \mu\text{rad}$; it has been taken into account in the simulation.

The electron histogram has a single maximum at $\tilde{\theta}_x \simeq 0$; on the contrary the positron histogram has a minimum for this $\tilde{\theta}_x$ value. This demonstrates clearly the influence of channeling : for both processes (SF and IBH), the electron-positron pairs are created near the atomic strings where the field (or the density of nuclei) is maximum ; the positron is then repelled (blocking effect) and the electron attracted by the string. The blocking effect should increase with decreasing positron energy : indeed, the exit angle of the positron with respect to the crystal axis is of the order of $[\theta_\gamma^2 + 2V(r_{in})/E^+]^{1/2}$. This trend is confirmed on Fig. 2.c, which shows a more pronounced dip for events selected by the additional cut $E_{out}^+ \leq 45 \text{ GeV}$.

Figure 3 displays the experimental and simulated distributions for the opening angle $\theta^{+-} = [(\tilde{\theta}_x^+ - \tilde{\theta}_x^-)^2 + (\tilde{\theta}_y^+ - \tilde{\theta}_y^-)^2]^{1/2}$ of the electron positron pair. This angle is not affected by the crystal misalignement and the beam size smearing effect. For comparison, a false θ^{+-} distribution obtained by taking electron and positron from different events

is drawn (dotted curve). The similarity between the "true" and the "false" distributions indicates that the initial collinearity of the electron and positron is almost forgotten, due to the scattering of the positron on the atomic strings and to the spiral motion of the channeled electron. In amorphous germanium, the r.m.s. of the θ^{+-} distribution would be $70 \mu\text{rad}$ at $E^+ = E^- = 50 \text{ GeV}$ (this r.m.s. is indicated by the arrow "A" in Fig.3). Scattering on atomic strings is thus more important than incoherent multiple scattering.

Figure 4 shows the energy distributions of the electron (4.a) and positron (4.b) (experimental data and simulation). The mean value of the electron energy is 10 GeV lower than that of the positron energy. The present experiment provides the first evidence of this asymmetry. It is due to the more intense radiation of the channeled electron and is most clearly seen in Figure 5 which shows the relative energy difference $\eta_{out} = (E_{out}^+ - E_{out}^-)/(E_{out}^+ + E_{out}^-)$ (this effect has also been recently calculated in Ref. [21]). For comparison, the corresponding distributions at the creation point are presented in dotted curves in Figs. 4 and 5 (E_{in}^+ , E_{in}^- and η_{in} taken from step 1 of simulation). We don't report here the pseudo invariant mass distribution obtained from these data. It is already published - see Fig.2 in Ref.[13].

To conclude this subsection, we observed that the agreement between the experimental and simulated energy spectra and angular distributions is quite satisfactory and the effects discussed in the introduction are demonstrated for the first time.

4.2. One-track events. The blocking effect would be seen more clearly if we could simultaneously determine $\tilde{\theta}_x$ and $\tilde{\theta}_y$ for the positron and the electron. In the preceding set of events only $\tilde{\theta}_x^+$ and $\tilde{\theta}_x^-$ were determined unambiguously. For $\tilde{\theta}_y$ we had two hits on the microstrip plane but we were unable to tell which one was the electron, which one was the positron. This ambiguity is not present in the case of one-track events. These events correspond to pair creation in which the electron hits the microstrip detector and the positron misses it, or vice-versa. The magnet and the MWPC give the energy and the charge of this particle. Figure 6 shows the scatter plot ($\tilde{\theta}_y$ vs. $\tilde{\theta}_x$) for the electron (6.a)

and the positron (6.b). The e^+ blocking effect is visible, but does not look particularly strong. This is partly due to the convolution in x and y with the transverse profile of the beam. To evaluate more clearly the magnitude of the blocking effect we present also in Figure 6 the θ_r distribution, where $\theta_r = [(\tilde{\theta}_x - \tilde{\theta}_{0x})^2 + (\tilde{\theta}_y - \tilde{\theta}_{0y})^2]^{1/2}$; $\tilde{\theta}_{0x} = -12.7 \mu\text{rad}$, $\tilde{\theta}_{0y} = 38.1 \mu\text{rad}$ are the coordinates of the center of the hole of Figs 6.b and 6.c and should coincide with the $\tilde{\theta}_{0x}$ and $\tilde{\theta}_{0y}$ defined earlier (we assume that the center of the hole is aligned with the $\langle 110 \rangle$ axis). We clearly see a depression at low θ_r for the positrons (Fig 6.e) and an enhancement for the electrons (Fig 6.d). The E^+ dependence is again confirmed by Figs 6.c and 6.f, which show a more pronounced hole for events with $E_{out}^+ \leq 45 \text{ GeV}$. We do not present simulation results for the one-track events, because of the large computing time needed : only a small fraction of the generated pairs leads to one-track events.

5. Discussion

The agreement between the data and the simulations (Figs. 2-5) indicates that the physics of pair creation in axial channeling conditions is basically understood.

Let us nevertheless discuss the validity of some approximations which have been made in our simulations.

1) *Incoherent pair production on target electrons of the crystal.* This contribution has not been included because it is a fraction $\sim 1/Z = 1/32$ of the total incoherent one, which is itself only $\sim 20\%$ of the total pair creation.

2) *Non zero impact parameter in incoherent pair creation.* In our simulation of IBH, we took the width of the $\vec{r}_{in}$ distribution equal to that of the thermal displacement : $\overline{r_{in}^2} = \overline{u_x^2} + \overline{u_y^2} \equiv 2u_{th}^2$. Actually $\vec{r}_{in}$ is the sum of the thermal displacement $\vec{u}$ of the atom and of the impact parameter $\vec{b}$ of pair creation with respect to the nucleus (Fig 7.a). Thus $\overline{r_{in}^2} > 2u_{th}^2$. On the other hand, the process is incoherent if $|\vec{b}| < \sqrt{2}u_{th}$ (see explanation below). Then $\overline{r_{in}^2} \sim 4u_{th}^2$. Working on a pure set of IBH simulated events, we have seen that doubling $\overline{r_{in}^2}$ leads to a slight attenuation of the blocking effect. However this was no

longer apparent in the total set.

3) *Inhibition of incoherent Bethe-Heitler mechanism in aligned crystal.* It has already been stated in the literature [16,22,23,24] that, in aligned crystals, incoherent electromagnetic processes should be suppressed at large impact parameter b , or equivalently at small momentum transfer q_T . Indeed, the incoherent part of the crystal potential $\delta V(t, x, y, z)$ is the difference between the instantaneous atomic potential $V_{inst}(t, x, y, z)$ and the continuous potential $V(x, y)$. In this difference, the long range parts of V_{inst} and V mutually cancel at $r \gg u_{th}$ (concept of *remnant atom* [22] or *double screening* [16]). Equivalently, one can say that the target atom must receive a momentum transfer $q_T > 1/u_{th}$ (in this section, $\hbar = c = 1$) to change the crystal wave function, whence the Debye-Waller factor $[1 - \exp(-u_{th}^2 q_T^2)]$. This implies that one should take $b_{max} \simeq (a_{TF}^{-2} + u_{th}^{-2})^{-1/2}$ as screening parameter of the Bethe-Heitler formula, instead of the Thomas-Fermi radius a_{TF} . This reduces the Bethe-Heitler cross section by $\sim 30\%$ [22]. However, since incoherent Bethe-Heitler and strong field mechanisms have similar values of $\overline{r_{in}}$, such a reduction of the IBH cross section has little influence on the transverse energy distribution. In fact, if we consider only the events generated by the strong field mechanism, the angular and energy distributions are almost the same as those obtained with the complete set of simulated events.

4) *Noncollinearity and "bilocality" of pair production in strong field.* Let us assume that energy-momentum conservation

$$E_\gamma = E_{in}^+ + E_{in}^- \quad , \quad \vec{P}_\gamma = \vec{P}_{in}^+ + \vec{P}_{in}^- \quad (1)$$

holds during the process of pair creation in strong field. Then the classical e^+ and e^- trajectories have to start at different distances r^+ and r^- from the string (tunneling mechanism shown in Fig. 7.b) and not at the same position $\vec{r}_{in}$, as assumed before. Eq. 1

leads to †

$$eV(r^-) - eV(r^+) \simeq e\mathcal{E} \times (r^+ - r^-) = \frac{M_{in}^2}{2E_\gamma}. \quad (2)$$

where $\mathcal{E}$ is the electric field and M_{in} is the initial invariant mass of the pair given by

$$M_{in}^2 = \frac{E_\gamma^2}{E^+ E^-} \times (m^2 + \vec{q}_T^2) \quad (3)$$

Here $\vec{q}_T = E^+(\vec{\theta}^+ - \vec{\theta}_\gamma) = -E^-(\vec{\theta}^- - \vec{\theta}_\gamma)$ is the relative transverse momentum of the pair [we give up collinearity, $\vec{\theta}$ stands for the bivector (θ_x, θ_y)]. We also assume that the transverse position

$$\vec{r} = (E^+ \vec{r}^+ + E^- \vec{r}^-) / E_\gamma \quad (4)$$

of the center-of-mass of the pair is equal to the transverse position $\vec{r}_\gamma$ of the photon. Then

$$eV(r^\pm) = eV(r_\gamma) \mp \frac{M_{in}^2}{2E_\gamma^2} \times E^\mp. \quad (5)$$

From this, we get the initial transverse energies of the e^+ and the e^- :

$$E_T^\pm = \pm eV(r_\gamma) + \frac{1}{2} E^\pm \theta_\gamma^2 \pm \vec{\theta}_\gamma \cdot \vec{q}_T - \frac{m^2}{2E^\pm}. \quad (6)$$

In the *collinear* and *local* approximation used in the simulation, $E_T^\pm$ was equal to the sum of the first two terms only. To get an idea of the error made, the third term (which averages to zero) is $\sim \pm 25$ eV for $\theta_\gamma \sim 50$ μ rad and $q_T \sim m$; the last term is -5 eV for $E^\pm = 25$ GeV. These corrections are still small compared to potential energy scale $eV_0 \simeq 300$ eV and we do not expect significant changes by introducing them.

6. Conclusion

The effects of electron channeling and positron blocking in pair creation inside an aligned crystal have been observed for the first time in this experiment. The electron angular distribution is maximum in the direction of the crystal axis ; on the contrary the

† In the following discussion, the subscript *in* for the variables $\vec{r}^\pm$, $\theta^\pm$, $E^\pm$ and $E_T^\pm$ will be dropped.

positron angular distribution shows a local minimum in this direction. As expected, this minimum becomes wider when low energy positrons are selected. It is also shown that the electron and the positron keep no memory of their initial collinearity.

The electron energy spectrum is definitely softer than the positron one. This can mainly be attributed to a very large fraction of channeled (below barrier) electrons. This effect would not be so strong if the electrons were not initially channeled and did not suffer transverse energy cooling due to radiation.

All the experimental distributions for two tracks events are in very good agreement with the simulated ones, which indicates that the physics of pair creation and radiation in crystal strong field is basically understood in this energy range.

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There is a misprint in the caption of fig. 2 : the number of events for the "crystalline" Monte Carlo is 2800.

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Figures Captions

Figure 1 : Experimental set-up. XTAL = Ge crystal; B1, B2 and B5 = magnets ;

D, AD, T1, T2, T3, T4 = scintillation counters ; μ S = silicon microstrips ;

TAG and CAL = lead-glass calorimeters.

Figure 2 : Angular distribution of emerging particles $dN/d\tilde{\theta}_x$. a) electron , b) positron , c) positron with the energy cut $E_{out}^+ < 45$ GeV.

• : experimental data ; full line : simulation.

Figure 3 : Distribution in relative electron-positron angle $dN/d\theta^\pm$.

• : experimental data ; full line : simulation ; dashed line : "false" e^+e^- combinations.

Figure 4 : Energy spectra of emerging particles.

• : experimental data ; full line : simulation ; dashed line : energy spectrum at the creation point (before radiation).

Figure 5 : Distribution of the energy asymmetry $\eta_{out} = (E_{out}^+ - E_{out}^-)/(E_{out}^+ + E_{out}^-)$.

• : experimental data ; full line : simulation ; dashed line : asymmetry distribution of the two-tracks events at the creation point (before radiation).

Figure 6 : scatter plot $\tilde{\theta}_x$ versus $\tilde{\theta}_y$ and radial angular distributions $dN/\theta_r d\theta_r$. See text for the definition of θ_r .

a,d) electron ; b,e) positron ; c,f) positron with the energy cut $E^+ < 45$ GeV.

(For better visualisation, Figs. d,e,f has been symmetrized about $\theta_r = 0$.)

Figure 7 : a) Impact parameter in incoherent pair production. $\vec{u}$ = thermal displacement of the nucleus ; $\vec{b}$ = impact parameter of the photon with respect to the nucleus ; $\vec{r}_{in}$ = distance to the axis (the initial transverse distance d^{+-} between the electron and the positron is negligible $d^{+-} \sim \hbar/(mc) = 386$ fm).

b) Tunneling mechanism of pair creation in strong field. $\vec{r}_\gamma$ = photon transverse position relative to the string ; $\vec{r}^\pm$ = transverse position of $e^\pm$. The dotted curves represent the nonclassical electron and positron paths during tunneling.

figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7