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STUDY OF e^+e^- PAIR CREATION BY 20-150 GeV PHOTONS
INCIDENT ON AN ALIGNED GERMANIUM CRYSTAL

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ABSTRACT

We report on absolute measurements of the orientation dependence of the e^+e^- pair production by 20-150 GeV photons aligned or nearly aligned with the $\langle 110 \rangle$ axial direction of a thin Ge crystal. The observed effects are very large, and are well described by theoretical predictions based on the existence of strong macroscopic fields in aligned crystals.

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We present the results obtained in the experimental study of e^+e^- pair creation by high energy photons incident along and around the $\langle 110 \rangle$ axial direction of a thin germanium crystal. The magnitude of the observed pair-creation enhancement and its angular dependence are well explained by theoretical predictions¹⁻³ that describe an aligned crystal as a source of strong "macroscopic" fields, which means that these fields extend over much larger distances than the field of a single atom.

Preliminary data, previously published by us⁴, had revealed the effect. However the experimental method used there was based on the detection of created positrons after they had been magnetically separated from electrons, and happened to yield only a lower limit of the pair creation rate in the 1.4 mm thick crystal we used. The reason is that the energy radiated by high energy electrons and positrons in a thin crystal is hugely increased for trajectories close to a string of atoms. This is supported by our direct observation⁵⁻⁷ of a radiation enhancement which is also an effect due to the strong electric fields encountered by these charged particles. In particular the mean energies radiated by 150 GeV positrons and electrons axially aligned along the $\langle 110 \rangle$ direction of the 1.4 mm Ge crystal are measured to be 70 and 108 GeV, respectively, instead of 9 GeV at random incidence. As a consequence the positrons created by aligned photons were able to lose so much energy in the crystal that they had a rather high probability of escaping detection.

Our new approach eliminates the problem just mentioned. Briefly (more details can be found in ref. 6) the experimental arrangement consists of a tagged photon beam produced from the bremsstrahlung of the incident electron beam in a lead foil 0.5 mm thick. This value balances the need for a large photon intensity and the necessity of keeping the emission of two photons by the same electron at a low level (a Monte Carlo simulation has been performed to account for two-photon

events in the analysis). The electrons transmitted through the above radiator are magnetically separated from the bremsstrahlung photons and directed onto the tagging spectrometer (a 21 radiation length thick lead glass calorimeter). For electron beam energies of 70, 150 and 200 GeV, the energy ranges of the tagged photons are 22-55, 55-130 and 90-155 GeV, respectively. The total pair creation rate is measured by means of two thin scintillators located just downstream from the crystal (the coincidence of the signals coming from the two scintillators allows one to eliminate the noise signals). Finally a calorimeter, placed in the photon beam direction, measures either the incident photon energy or the sum of the energies of a pair created in the crystal and the photons it may radiate there. A pair creation event is considered legitimate only when the sum of the energies deposited in the tagging spectrometer and in the calorimeter equals the energy of the primary electron beam.

The Ge crystal is the same as in our previous experiment. Its thickness of 1.4 mm is quite appropriate since preliminary measurements have shown that the amount of matter encountered by incident photons along the beam line is equivalent to about 0.5 mm of amorphous germanium. On the other hand the pair creation yield is always low enough ($< 30\%$, then far from the saturation of the yield one would observe for increasing crystal thicknesses) to allow an accurate determination of the pair creation rate.

The experimental set up has been tested with a non-crystalline target. Ordinary pair creation rates have been measured to be independent of the photon energy and in close agreement (within 3%) with the predicted Bethe-Heitler (BH) rate (due to the macroscopic nature of the studied effect, the experimental data, in random as well as in alignment conditions, are to be expressed in rates per unit length rather than in cross sections).

In **figure 1** we show our results on the energy dependence of the pair creation rate when high energy photons are incident along the $\langle 110 \rangle$ axial direction of the 1.4 mm crystal, cooled to 100 K. The pair production rates are expressed in units of the BH value. The experimental data obtained successively for three energies of the primary electron beam are seen to overlap nicely. The pair creation rate is nearly equal to the BH value at 30-40 GeV and then increases sharply with energy.

Also shown are the theoretical predictions of Kimball and Cue¹. These are based on two approximations that give a simple view of the process and make the calculations tractable. The first one is the continuum approximation in which the discrete nature of atomic strings is ignored, and the crystal fields are obtained by averaging the atomic potentials along the direction parallel to the string. This approximation has been extensively and successfully used in channeling studies. The second approximation (the uniform field approximation UFA) assumes that the transverse electric field experienced by a particle travelling parallel to a major axial direction remains constant over a pathlength larger than the formation length of the conversion process. In this connection the crystal fields were calculated from the Doyle-Turner approximation of the Hartree-Fock potential and include the averaging due to the thermal motion of the crystal atoms.

The process of pair creation by high energy photons in strong uniform electromagnetic fields has been described theoretically many years ago⁸, but there had been no experimental study of this process since macroscopic strong fields such as crystal fields seen by relativistic particles were not previously considered. In the present case the total pair creation rate of perfectly aligned photons can be calculated by summing up the contributions for the whole range of electric fields encountered in the vicinity of an atomic row. The results of the UFA calculations are displayed as a solid curve in **figure 1**. This curve lies below the experimental

values and the predicted rate goes down to zero with decreasing energy, which is quite unrealistic. However the contribution of individual target atoms cannot be ignored. If one accounts for it by adding the BH value to the UFA rate one gets the dashed curve of **figure 1**, which agrees quite well with the data. Kimball and Cue⁹ have recently shown that individual atoms contribute significantly only because of their displacement away from their equilibrium position. Using an analogy with the contribution of individual atoms to the diffraction of X-rays by a crystal, their calculation leads to a contribution of 72% only of the BH value for our experimental conditions. In any case the agreement between experiment and theory is quite remarkable. These measurements yield the first observation of pair production due to a macroscopic field. It must be noted that for a given axial direction the crystal field decreases when the thermal motion increases. Therefore we have performed the experiment at the crystal temperature of 100 K.

In **figure 2** we show the experimental orientation dependence of the pair production rate (still expressed in BH units) in the vicinity of the $\langle 110 \rangle$ direction for five groups of photon energies. The angle θ between the photon beam and the $\langle 110 \rangle$ direction was varied so as to avoid planar effects. The beam direction was kept parallel to the plane making an angle of 0.1 radian with the (001) plane (the knowledge of this angle is necessary to the evaluation of the coherence effects between neighbouring atomic rows that will be discussed later). The enhancement of the pair production rate over the BH value is seen to extend to large θ values. In each interval of photon energy the maximum rate is not obtained at $\theta = 0$ but at an angle θ_m . When the photon energy γ (expressed in units of the electron mass) increases, θ_m decreases as γ^{-1} . However the pair creation rate increases much faster with energy at 0° than for any off axis incidence. From the absence of any structure at small θ values it may be concluded that the pair production process is not linked to the probability that the created electron be channeled, in opposition

with the earliest predictions of the effect¹⁰ (the critical angle for channeling of 60 GeV electrons in $\langle 110 \rangle$ Ge is about $100 \mu\text{r}$, and the angular dispersion of the pair - well characterized by γ^{-1} - is less than $5 \mu\text{r}$ for 120 GeV photons).

Also shown in **figure 2** are theoretical predictions on the angular dependence of pair creation. One set is the prediction of the standard theory of coherent pair production (CPP) that incorporates the crystal periodicity in the transverse plane and is based on the first Born approximation¹¹. Note that the contribution of incoherent pair creation is included in the CPP theory and also that the fine structure it predicts for a given photon energy is washed out here because of the wide photon energy range associated with each curve. The predictions (dotted curves) are in good agreement with the experimental rates obtained at large θ values and also yield a maximum at θ_m . The disagreement observed at small θ values is expected since the Born approximation is known to fail at small angles. In order to describe pair creation in this angular range, a set of calculations has been recently performed¹², which is based on the idea that the continuum crystal field experienced by misaligned photons is no longer constant but time dependent. It is an extension of the semi-classical theory of Baier et al.¹³ of electromagnetic conversion processes in non-uniform macroscopic fields. Based on the single string approximation, these calculations do not account for the lattice periodicity in the transverse plane. They are shown as solid curves in **figure 2**. As for perfect alignment, the contribution of ordinary pair creation has been included by adding one BH unit to the calculated values. The calculations are in very good agreement with the experimental data for small θ values whereas they underestimate the pair creation rate for large θ values, which is not surprising since this single string model cannot account for coherence effects of string crossings as CPP does. The values obtained at 0° coincide with the theoretical values of **figure 1** since the two calculations are identical in this case. The maximum rate at θ_m is

quite well reproduced both in amplitude and position, which shows that the existence of the maximum is not due to the details of the crystal structure. In fact it results from the conflict between two requirements of the process : the transfer of longitudinal momentum from the atomic row to the created particles (in order to conserve energy and momentum), which is easier at large angles, and the need for a certain pathlength (at least of the order of the formation length) in the strong field of an individual atomic string, a condition which is fulfilled at small angles. Estimates¹⁴ of θ_m founded on these arguments lead to the value $(\alpha\gamma)^{-1}$, where α is the fine structure constant.

This is contrary to the case of photon radiation from a positron or electron moving nearly parallel to an axis. Our previous study⁷ has shown that the energy radiated by electrons or positrons is maximum for perfect alignment (if one excludes channeling effects that produce a very narrow angular structure which is a peak for electrons and a dip for positrons). This can be explained by the fact that the synchrotron-like radiation process is maximum at 0° because the time spent by the particles in the strong field is the largest in this case.

It is also interesting to compare the angular widths of the enhancements observed in pair creation and radiation. Our data show that radiation decreases much more rapidly with angle than pair creation. The reason for that is that the radiation of a low energy photon requires a large pathlength in the field of a given atomic string, and is preferentially inhibited when the particle trajectory makes a large angle with the axis¹⁵.

However both pair creation and radiation exceed the random yield over a large angular domain. This means that an electromagnetic shower should develop in an aligned crystal over a much shorter distance than in a corresponding amorphous material. This could be of great practical interest for the detection of very high energy particles.

Finally it is worth mentioning the recent suggestions^{16,17} that the sharp enhancement of pair creation could be used for localizing high energy photon sources of the universe. Telescopes flown on satellites and based on this new effect could possibly improve the angular resolution of current measurements by several orders of magnitude.

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FIGURE CAPTIONS

Figure 1

Energy dependence of the total pair production rate when photons are incident along the $\langle 110 \rangle$ axial direction of a 1.4 mm thick Ge crystal cooled to 100 K. The three different symbols correspond to three different energies of the primary electron beam (see text). The solid curve represents the theoretical predictions of the uniform field approximation. The dot-dashed line corresponds to the rate in an amorphous target (Bethe-Heitler theory). The dashed curve gives the sum of the calculated rates of the coherent and incoherent processes.

Figure 2

Angular scan of the total pair production rate around the $\langle 110 \rangle$ direction of a 1.4-mm thick Ge crystal cooled to 100 K. Each data point corresponds to an integration of the rate over the indicated photon energy range. The solid curves correspond to the theoretical predictions based on the time-dependent field model discussed in the text. The dashed curves correspond to the coherent pair production calculated in the frame of the Born approximation. The two upper curves correspond to the 120-150 GeV range of incident energies, and the two lower curves to the 40-60 GeV range. The dot-dashed line corresponds to the Bethe-Heitler rate in an amorphous target.

Fig. 1

Fig. 2