DETECTOR OF SUPERHARD PHOTONS USING ALIGNED SINGLE CRYSTALS

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Abstract

The effects of considerable amplification of the pair production by photons and of radiation of charged particles in aligned single crystals are suggested to use for the creation of a comparatively simple ultra-high-energy photon detector ($\omega > 100$ GeV) with high angular resolution.

We would like to attract attention to the possibility of creating a relatively simple ultrahigh-energy photon detector ($\omega > 100$ GeV) with high angular resolution (better than 10^{-3}). It is suggested to make use of the physical phenomenon of electron-positron pair production by ultrahigh-energy photons in the fields of the single crystal's axes. It is important that the probability of this process W_e^{CF} at ultrahigh energies exceeds considerably that of the pair creation by photons in a non-aligned crystal; the latter is close to the pair creation probability in an appropriate amorphous medium[1-3] W_{BH}. The maximum gain r_{max} is given in Table 1. The basic practical interest appears to be of Si and Ge single crystals for which the exceeding of W_e^{CF} over W_{BH} is rather large. This is the circumstance which is to be used when creating the detector.

Let us present the necessary information on the properties of the phenomenon to be used[1-3]. At small angles of incidence of a photon $\vartheta_0 \ll V_0/m$ (ϑ_0 is the angle between the photon momentum and the axis, V_0 the scale of the axis potential, and m is the electron mass) the probability of the pair production by the photon W_e^{CF} vs. the photon energy is demonstrated in Fig. 1. At low energies the probability W_e^{CF} is exponentially small, while at $\omega = \omega_t$ it equals the magnitude of W_{BH} and then grows up to its maximum value $W_e^{CF}|_{max} = r_{max} W_{BH}$ (see Table 1). The effect under discussion should be used at the energies when $W_e^{CF} \gg W_{BH}$. For definiteness, we chose the energy $\omega = \omega_{10}$, when $W_e^{CF} = 10 W_{BH}$; the values of ω_{10} are also given in Table 1. The spectrum of the particle pair, produced in the energy range in question is rather smooth in the interval $0.1 < \varepsilon_\pm/\omega < 0.9$ ($\varepsilon_\pm$ are the electron and positron energies respectively), see Fig. 2 in Ref.[3]. It is seen from the comparison of curves 1 and 2 in Fig. 1 that when going from one main axis to another the probability W_e^{CF} changes but this change is not too significant. When decreasing the temperature from room to the boiling point of nitrogen the W_e^{CF} increases, at a given energy (see Fig. 1 in Refs[2,3]) on that part of the curve, where W_e^{CF}, as an energy function, increases; meanwhile the asymptotic values of W_e^{CF} are weakly temperature-dependent. The electrons and positrons moving near the single crystal's axes radiate intensively. In the region of very high energies we are interested in this radiation is of the magnetic bremsstrahlung nature. Fig. 1 also presents the energy dependence of the inverse characteristic length of the energy losses $L_{ch}^{-1} = \frac{1}{\varepsilon}\frac{d\varepsilon}{dl}$, where l is the penetration depth of a particle into the crystal (curves 3, 5). During the motion near the axis the quantity L_{ch} is tens times shorter than the length on which the particle in the non-aligned crystal loses its energy[1,4] $L_{rad} = 1/W_{BH}^{\gamma}$ (the numerical calculations of the radiation and pair creation probabilities in a cooled Ge are also contained[5]). Since the characteristic angles in the pair creation and radiation processes $\sim m/\omega$ is considerably smaller than the angle V_0/m, the high-energy photon with the angle of incidence $\vartheta_0 \lesssim V_0/m$ causes, in the single crystal, a specific shower evolving on the length tens times shorter in comparison with that in the amorphous medium[2].

Figs 2 and 3 illustrate the orientation dependence of the pair creation probability $W_e(\vartheta_0)$ relative to the

Table 1

Parameters of the Potential and Some Quantities Characterizing the Pair Creation

Crystal	Axis	T	V_0, eV	η	a_s	x_0	ω_t, GeV	ω_{10}, GeV	ω_m, TeV	$r_{max} = \frac{W_e^{CF}|_{max}}{W_{BH}}$
$C_{(d)}$	⟨111⟩	293	29	0.025	0.326	5.5	90	200	10	156
$Si_{(d)}$	⟨111⟩	293	54	0.150	0.299	15.1	150	350	14	68
$Si_{(d)}$	⟨110⟩	293	70	0.145	0.324	15.8	120	250	12	78
$Ge_{(d)}$	⟨111⟩	293	91	0.130	0.300	16.3	100	400	7.9	25
$Ge_{(d)}$	⟨110⟩	280	110	0.115	0.337	15.8	70	300	7.0	29
$Ge_{(d)}$	⟨110⟩	100	114.5	0.063	0.302	19.8	50	200	4	29
W	⟨111⟩	293	417	0.115	0.215	39.7	22	600	1.4	10.5
W	⟨111⟩	77	348	0.027	0.228	35.3	13	400	1.1	10.8

Note: V_0, η, a_s, x_0 are the parameters of the potential[1,2,3], ω_t is the photon energy at which the pair creation probability in the axis field is equal to the value in the amorphous medium W_{BH}, ω_{10} is the photon energy at which $W_e^{CF} = 10 W_{BH}$, ω_m is the photon energy where W_e^{CF} achieves its maximum value, and r_{max} is the maximum magnitude of the effect.

⟨110⟩ axes in Si and Ge respectively, at various photon energies. These results have been obtained within the framework of a general description of the orientation phenomena at the pair creation in single crystals[3]. To

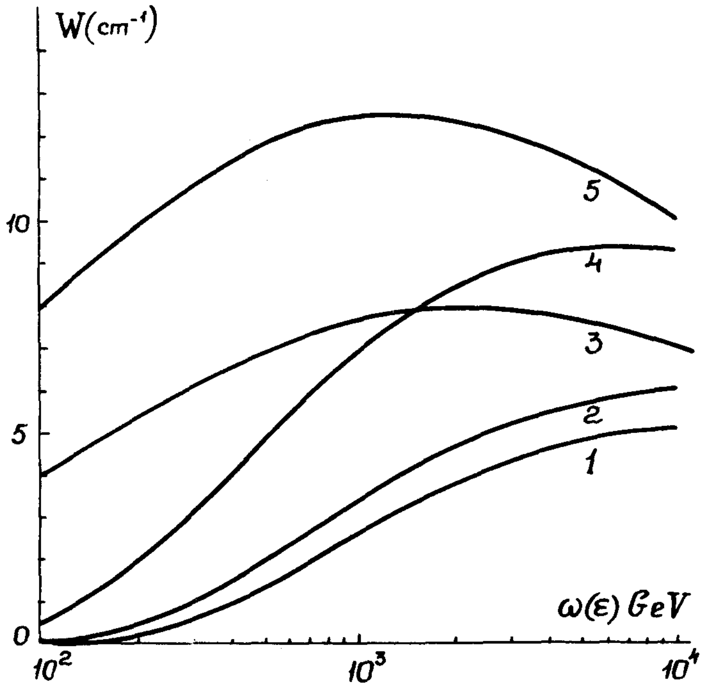

Fig. 1. The total pair creation probability vs. the initial energy for Si⟨111⟩ (curve 1), for Si⟨110⟩ (curve 2) and for Ge⟨110⟩ (curve 4), as well as the inverse characteristic length of the energy losses for Si⟨110⟩ (curve 3) and for Ge⟨110⟩ (curve 5), at room temperature.

describe the behaviour of the function $W_e(\vartheta_0)$, we introduce the angles ϑ_0^{BH} and $\vartheta_0^{(1/2)}$, given in Table 2. By definition, 1) $W_e(\vartheta_0^{BH}) = W_{BH}$, i. e. the angle ϑ_0^{BH} may be regarded as the boundary at which the coherent effects manifest themselves. For Si and Ge the approximate formula $\vartheta_0^{BH} \simeq 30V_0/\sqrt{\omega W_{BH}}$ holds (here V_0 is taken in eV, ω in MeV and W_{BH} in cm^{-1}) and 2) $W_e(\vartheta_0^{(1/2)}) = (1/2)W_e(\vartheta_0=0)$, i. e. the angle $\vartheta_0^{(1/2)}$ characterizes the angular resolution. As it is seen from Figs 2 and 3, near the threshold chosen $\omega \gtrsim \omega_{10}$ the pair

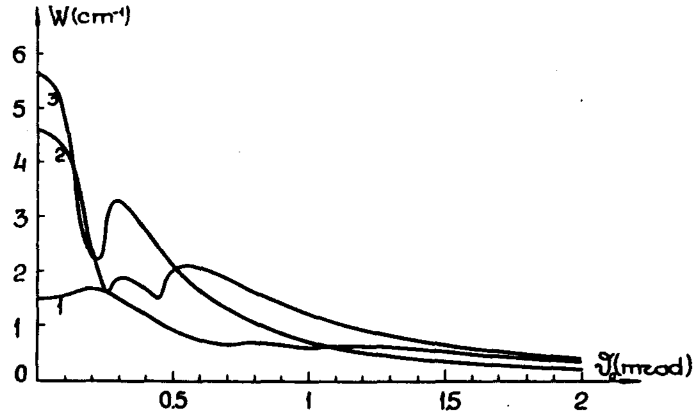

Fig. 2. The pair creation probability vs. the angle of incidence relative to the ⟨110⟩ axis for Si, $T=293$ K for $\omega=0.4$ TeV (curve 1), for $\omega=2$ TeV (curve 2) and for $\omega=5$ TeV (curve 3).

creation probability in the axis field ($\vartheta_0 < V_0/m$) is close to the coherent creation probability ($\vartheta_0 > V_0/m$) so that there is a wide plateau in the orientation dependence and, correspondingly, the angle $\vartheta_0^{(1/2)}$ is fairly large. As the energy increases, at small angles the peak in the function $W_e(\vartheta_0)$ appears. This peak grows up to $\omega \simeq \omega_m$ and, as it is seen in Figs 2, 3 and in Table 2, its width decreases.

Table 2

The Angles Characterizing the Orientation Dependence (in mrad) for the Pair Creation Process

Si⟨110⟩			Ge⟨110⟩		
ω, TeV	ϑ_0^{BH}	$\vartheta_0^{(1/2)}$	ω, TeV	ϑ_0^{BH}	$\vartheta_0^{(1/2)}$
0.4	11	1,2	0.3	10	2
2	6	0,6	1	6	1.2
5	4	0,4	3	4	0.7

Our detector is a matrix of aligned single crystals of small thickness L. For definiteness, we take Si with $L=1$ cm $=(1/13)L_{ph}^{BH}$ ($L_{ph}^{BH}=1/W_{BH}$). When the photon moves at a large angle to the axis the pair creation probability is, correspondingly, low, whereas when the photon is incident inside the characteristic angle discussed above the pair creation probability is roughly equal to unity, beginning with $\omega \gtrsim \omega_{10}$. The angular resolution of the detector is energy-dependent and is characterized by the angle $\vartheta_0^{(1/2)}$ (Table 2). The particles of the produced pair are detected by a detector of small thickness (in radiation lengths), for example, by a thin scintillator. In addition, there is the possibility of detecting the signal directly from the single crystals. Already at

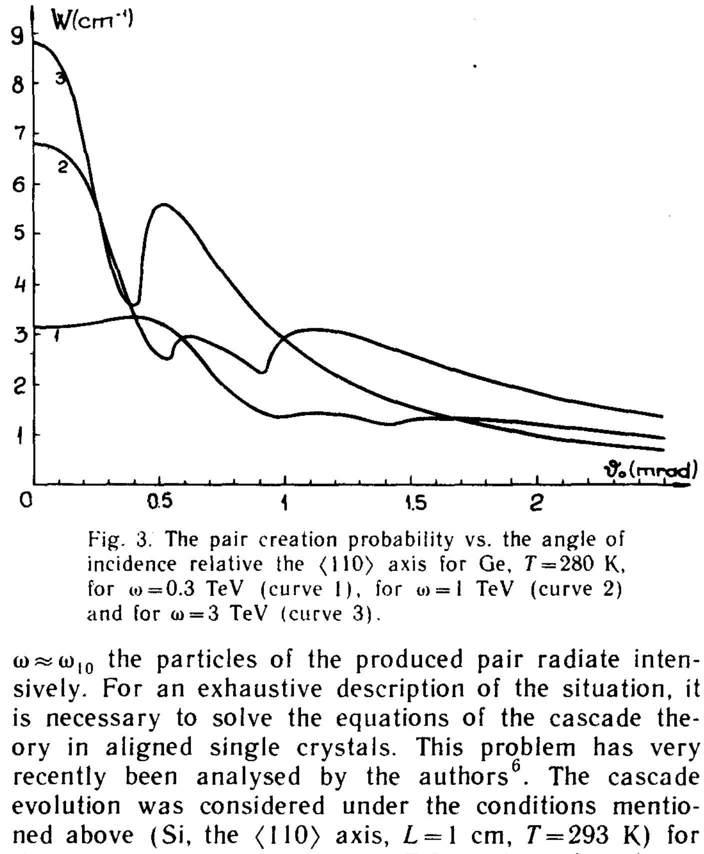

Fig. 3. The pair creation probability vs. the angle of incidence relative the ⟨110⟩ axis for Ge, $T=280$ K, for $\omega=0.3$ TeV (curve 1), for $\omega=1$ TeV (curve 2) and for $\omega=3$ TeV (curve 3).

$\omega \approx \omega_{10}$ the particles of the produced pair radiate intensively. For an exhaustive description of the situation, it is necessary to solve the equations of the cascade theory in aligned single crystals. This problem has very recently been analysed by the authors[6]. The cascade evolution was considered under the conditions mentioned above (Si, the ⟨110⟩ axis, $L=1$ cm, $T=293$ K) for the energy range $\omega_t < \omega_0 < 10$ TeV. When the photon energies are $\omega \gg \omega_t$ the cascade evolves due the particular mechanism in the field of the single crystals axes and for $\omega \lesssim \omega_t$ the particles radiate mainly in the field of the axes but the pair creation is due to the Bethe-Heitler mechanism (mixed cascade). The photon energy $\omega_f = 100$ MeV was taken as the lower boundary, this corresponds to the effective threshold of pair photoproduction in the matter. The lower boundary of charged particles energy was $\varepsilon_f = 10$ GeV (if $\varepsilon < 10$ GeV, the photons with energy $\omega < 100$ MeV will be mainly radiated). We have obtained the number N_γ of outgoing photons with $\omega > 100$ MeV: $N_\gamma \simeq 40$, 90 and 150 for the initial photon energy $\omega_0 = 0.4$ TeV, 1 MeV and 2 TeV, respectively. The number of charged particles N_{ch} is $N_{ch} \simeq N_\gamma / 11$. One should emphasize that the authors[4] have made a quite satisfactory description of the experiment[7] on the radiation of electrons with the initial energy $\omega_0 = 0.15$ TeV, which are incident near the $\langle 110 \rangle$ axis of the cooled ($T = 100$ K) Ge single crystal; note that on the thickness $L = 1.4$ mm, i. e. $L \simeq (1/2) L_{ph}$ ($L_{ph} = 1/W_e^{CF}$, $\omega_0 \sim \omega_{10}$), the electron emits approximately 10 photons and loses about 75% of its energy. These results are confirmed by a more detailed analysis[6]. Thus the above calculations dealing with the multiple radiation of photons by the charged particles moving near the single crystal's axis are well-grounded, in the indicated sense, experimentally. The said above enables one to suggest the following possible scheme of the detector. A standard (for example, lead, tungsten) converter of L_{ph}^{BH} thickness is placed behind the thin scintillator which is fixing the fact of pair creation in the single crystal. In this converter the emitted photons are transformed into the pairs, and a very strong signal caused by 80—300 particles will be registered in the second scintillator next to the converter (corresponding chart is sketched in Fig. 4). After a comprehensive

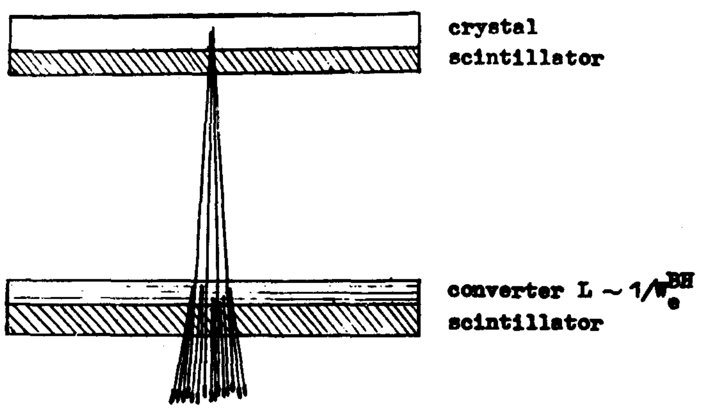

Fig. 4. Rough drawing of the detector. The photon, moving along the axes converts into the pair (plus some additional pairs) and the produced charged particles radiate many photons. The charged particles produced in the crystal are detected by the first scintillator. In the convertor photons produce e^+e^- pairs, so that a very strong signal is detected by the second scintillator. A distance between parts depends on the needed angular resolution.

analysis of the cascade process[6] we see that there is a possibility to measure the energy of an initial photon basing upon the properties of this signal.

In high energy physics this device can be employed as a thin directed converter. As an illustration, let us consider a W crystal ($\langle 111 \rangle$ axis) of thickness $L = 0.2$, $L_{ph} \simeq 0.9$ mm. Beginning with the photon energy $\omega \simeq (50 \div 80)$ GeV the pair creation probability in it will be of the order of unity (depending on the temperature) at a relatively wide expectance angle $\vartheta_0^{(1/2)}$ (see[3] Fig. 5). Similarly, the electrons that are incident on this converter near the axis will radiate extensively (the characteristic angles for radiation and pair creation are of the same order). A rough drawing of the single crystal system inserted in some universal detector for colliding beams experiment is presented in Fig. 5. When outgoing particles escape inside small solid angle (fixed target experiments, HERA experiments, etc.) the single crystal system may be also very useful (see

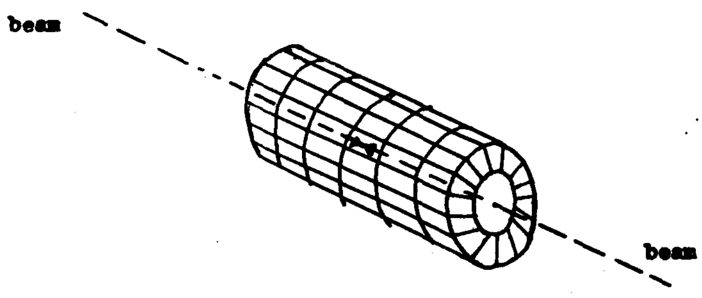

Fig. 5. Single crystal insertion in the universal detector gives the possibility to detect $e^\pm$ and (with energy starting from 10 GeV (for W) and distinguish them from hadrons.

Fig. 6). The main advantages of single utilization for particle detection are: 1) detection and separation of electrons and photons from hadrons; 2) measurement of $e^\pm$, γ energies.

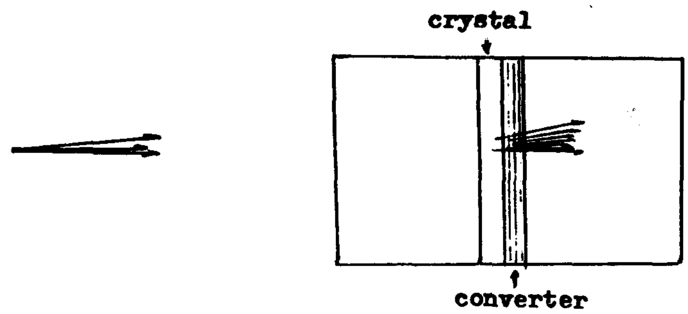

Fig. 6. Single crystal insertion into the detector for fixed target experiments. The produced pairs may be detected by any tracking device.

Another interesting region of applicability of the detector is γ-astronomy. We would like to discuss the question of the detection of superhard photons from a point source, for example, Cygnus X3. The data on its emission of photons with an energy of 1 TeV$\div 10^3$ TeV have been obtained by observing the Cherenkov radiation in the atmosphere, wide atmospheric showers, as well as the muons in deeply underground detectors. The experimental data obtained are quite different. It is recognized that the averaged flux of photons with an energy higher than ω behaves as L/ω and the flux[8] is $I(\omega > 250 \text{ GeV}) = 10^{-9} \div 10^{-10}$ photons/cm^{2}s. With such a flux, a Si detector (the $\langle 110 \rangle$ axis) of 1 m^2 area will register 300—30 events with $\omega > 250$ GeV per year. The detector should be oriented to the source with an accuracy of about 10^{-3}. The events of interest can be separated using the system described above.

The authors are deeply thankful to A.N. Skrinsky for numerous helpful discussions and his attention to the work presented. We are indebted to A.G. Chilingarov for discussion.

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Discussion

W. Vernon. What is the effective solid angle of acceptance for the crystal or a detector?

V.N. Baier. Typical angular resolution is at level from several milliradians in W down to 10^{-4} radians, depending on the photon energy. This defines the solid angle for the selected direction where sharp increase in interaction cross section occurs.

V. Sörgel. You presumably require very high quality crystals, don't you?

V.N. Baier. No. Of course there must be some quality. In the experiments made so far the level of an internal curvature in single crystals was about 10^{-5}. What is really necessary, say for W, is about 10^{-3}. So you see that the requirement for crystal quality are rather weak. But of course it must be a single crystal.

T. Toohig. How well do the crystal in the matrix need to be aligned?

V.N. Baier. There are many methods to achieve the necessary alignment accuracy. One of the possible ways is to use for the alignment this very effect which is so large.

С.И. Середняков. Каковы ионизационные потери электронов в условиях этого усиления?

В.Н. Байер. Никаких изменений в ионизационных потерях по сравнению со стандартным режимом не происходит. Ионизационные потери не связаны с этим механизмом и поэтому не меняются. Обсуждаемый механизм является дополнительным к уже имеющимся. Уже проведены первые эксперименты в этой области и после некоторой предыстории теперь экспериментальные данные согласуются с теорией. Наблюдаемая вероятность есть сумма бете-гайтлеровской и вероятности данного эффекта. Так что этот эффект является добавочным, хотя и очень большим.