# DYNAMIC RADIATION GENERATED IN CRYSTALS BY PARTICLES WITH ULTRARELATIVISTIC ENERGIES

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In [5, 6] we reported observation of generation of x-rays in thin rock-salt and diamond crystals by passage of electrons with energies 1 - 2.46 GeV. We have noted at the same time that the observed phenomenon cannot be explained within the framework of the usual transition radiation, since the intensity of the photons generated in the crystals is about 100 times larger than in films of amorphous matter (mylar, polyethylene, and foamed plastic) [1]. This cirstance is strong evidence that we have actually observed a new mechanism for radiation by a fast charged particle, wherein the number of photons generated in the investigated frequency interval increases furthermore with increasing primary-particle energy, unlike the known mechanism of the bremsstrahlung type.

This new mechanism of radiation by a charged particle was theoretically predicted by one of us (G.M. Garibyan), and this in fact initiated the experiments in this direction. The physical mechanism whereby such radiation is produced is connected with the diffraction of the field of the charged particle moving at constant velocity by the individual atoms of the crystal lattices; for fields whose wavelengths are much shorter than the interatomic distances.

We present here the results of further investigations of this phenomenon. Figure 1 shows a diagram of the experimental setup. A very weak current of electrons, with energy variable from 1.3 to 4.0 GeV, passed through a vacuum beam guide and a streamer chamber (SC) measuring 80 × 20 × 10 cm. The streamer chamber was filled with Ne + 10% Xe at normal pressure. Temperature counters $S_2$ and $S_3$ were connected for anticoincidence with a scintillation counter $S_1$ having an aperture of 10 mm diameter, through which the stream of primary electrons passed. Placed at the output of the aperture was a radiator R, in the form of a thin crystalline plate of NaCl, LiF, or mica. To eliminate the background produced by the bremsstrahlung, the crystalline plate was replaced each time by an amorphous radiation with an equivalent number of radiation lengths of matter.

The average number of photoelectrons $\eta_{eff}$ or $\eta_{backgr}$ per primary electron was determined by counting the total number of photoelectrons and was referred to the total number of single high-energy electrons registered in the chamber.

In a number of cases, to increase the reliability with which the number of the photoelectrons was determined and to separate them from the δ-electrons produced by the primary electron in the gas of the chamber, a magnetic field of $3.5 \times 10^3$ Oe was applied past the radiator and deflected the primary particle by 3 - 4 cm. The photons generated in the crystals and traveling at a small angle to the primary particle then

Fig. 1

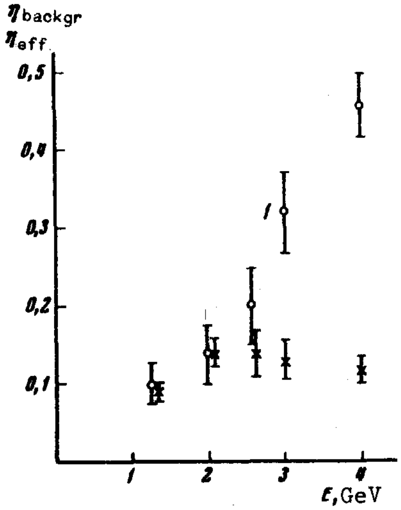

Fig. 2

continued to move in the same direction and produced in the streamer chamber photoelectrons at such distances, that they could be distinguished without any doubt from the $\delta$-electrons. The table lists the results of the measurements with the different radiators. As can be seen from this table, the crystalline radiator gives in all cases a much larger average number of photoelectrons than the corresponding amorphous radiator (on a per-layer basis).

Figure 2 shows a plot of $\eta_{\text{eff}}$ against the energy of the primary electrons, with the background subtracted (curve 1), for a mica radiator consisting of 7 layers $10^{-2}$ cm thick, 20 layers $4 \times 10^{-3}$ cm thick, and 20 layers $2 \times 10^{-3}$ cm thick (total thickness 1.9 mm). Curve 2 in the same figure shows the results of measurements for $\eta_{\text{backgr}}$. It follows from this figure that at all primary electron energies $\eta_{\text{eff}}$ not only greatly exceeds $\eta_{\text{backgr}}$, but unlike the latter it increases rapidly with increasing primary-electron energy.

It should be noted that the observed number of photoelectrons in the gas of the streamer chamber amounts to only a fraction of the total number of photons produced in the radiator. In fact, first, the current will decrease because only 15%, 53%, and 82% of the photons of energy 20, 30, and 50 keV, respectively, will leave a radiator of total thickness 1.9 mm. Second, the efficiency with which such photons are registered by a streamer chamber is less than 100% and decreases sharply with increasing photon energy.

We note that by subtracting $\eta_{\text{backgr}}$ we have in fact eliminated only the Bethe-Heitler part of the bremsstrahlung. However, the electron produces also coherent bremsstrahlung on passing through the crystal lattice [2 - 4]. But to produce coherent bremsstrahlung the direction of electron motion must be suitably collimated relative to the crystal axes. For photons of the energies of interest to us, this angle is $\sim 5 \times 10^{-8}$ rad. On the other hand, it is known that a single crystal consists of individual ideal crystallites or blocks containing approximately $10^3$ - $10^4$ atomic layers, and these blocks are turned relative to one another through angles $\sim 10^{-4}$ - $10^{-3}$ rad. It is therefore clear that coherent bremsstrahlung of energy of several dozen keV can be produced only by those individual blocks that are properly oriented relative to the direction of motion of the primary electron. It turns out that in a thickness of 1.9 mm there is approximately only one such block. Calculations yield that, say, a 4-GeV electron produces in one block about 5 photons with energy on the

| Radiator material | NaCl | NaCl | NaCl | Mica | Mica | LiF | Mylar |
|---|---|---|---|---|---|---|---|
| Thickness of each layer | 2.5 | 20 | 0.6 | 0.1 | 0.05 | 0,25 | $10^{-2}$ |
| Number of layers | 2 | 1 | 1 | 7 | 1 | 6 | 1700 |
| Distance between layers, mm | 50 | – | – | 1 | – | 1 | 0.3 |
| Electron energy, GeV | 2,5 | 2,5 | 4,0 | 4,0 | 4,0 | 4,0 | 2,46 |
| $\eta_{\text{backgr}}$ | 0.14 ± 0.04 | 0.14 ± 0.04 | 0.136 ± 0.02 | 0.14 ± 0.02 | 0.09 ± 0.01 | 0.14 ± 0.02 | 0,1 ± 0.01 |
| $\eta_{\text{eff}}$ with background subtracted | 0.35 ± 0.03 | 0.27 ± 0.08 | 0.2 ± 0,04 | 0.33 ± 0,04 | 0.12 ± 0,03 | 0.2 ± 0,04 | 1,2 ± 0,15 |

order of 10 keV, and this number does not depend on the energy of the primary electrons. The latter is a consequence of the fact that the thickness of the block is smaller than the coherence length. We now take into account the fact that the angle scatter of the electrons incident on the crystal lattice was $\sim 10^{-3}$ in our experiments. Therefore only $5 \times 10^{-5}$ of the electrons passing through the crystal can produce coherent bremsstrahlung. Consequently, the contribution of coherent bremsstrahlung amounts to $\sim 2.5 \times 10^{-4}$ quantum per primary electron in the crystal under consideration. Thus, in spite of the fact that we used relatively thick crystals, in our experiments the coherent bremsstrahlung was negligibly small, since the crystals were not sufficiently ideal.

Calculation of the Bethe-Heitler bramsstrahlung gives for these crystals about $10^{-3}$ photon per primary electron. On the other hand, it is seen from the table and from Fig. 2 that the background measured by us was of the order of $10^{-1}$ photon per primary electron. We can therefore conclude that $\eta_{\text{backgr}}$ is due to the background in the laboratory and should not depend on the thickness and type of radiator, as is also seen from the table.

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# FEASIBILITY OF OPTICAL ORIENTATION OF EQUILIBRIUM ELECTRONS IN SEMICONDUCTORS

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The first experiments on optical orientation of free carriers in semiconductors were performed recently [1 - 4]. In materials of p-type, with which most of the experiments were performed, the oriented electrons were those propelled into the conduction band by circularly polarized light (there is practically no orientation of holes in the valence band, owing to the rapid relaxation of their spin). Thus, only the spins of non-equilibrium carriers become oriented. Their number is proportional to the intensity of the light, but the degree of orientation does not depend on the intensity. The phenomenon is analogous to optical orientation of excited atoms of a gas [5].

The purpose of the present paper is to show that in semiconductors, just as in a gas, it is possible to attain optical orientation of the ground state (optical pumping). Namely, in an n-type semiconductor (with a simple conduction band that is doubly degenerate in the spin) it is possible to obtain a considerable degree of electron orientation even at exciting-light intensities at which the concentration of the non-equilibrium carrier is still small