Orientational dependence of the yield of bremsstrahlung photons of maximum energy in crystals

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Experimental and theoretical investigations were made of the orientation dependence of the differential cross section of the bremsstrahlung of hard photons on the entrance angle of ultrafast electrons into a single crystal. A strong decrease of the yield of bremsstrahlung photons with maximum energy near zero entrance angle is predicted and observed.

Coherent bremsstrahlung of electrons in a crystal leads to the appearance of maxima and minima in the spectrum of the emitted photons.[1–3] Perturbation-theory calculations lead to the appearance of a characteristic length over which the process takes place, $l \sim (2E_0/m)(1-x)/x$, where m and E_0 are the mass and energy of the initial electron, $x=\omega/E_0$, and ω is the energy of the emitted photon. At $x \sim 0.1$—0.3 we have $l > a$, where a is the lattice constant, and the process proceeds coherently. At $x \sim 1$ we have $l < a$ and the atoms of the crystal emit independently—there is no dependence on the angle at which the electrons enter the crystal. However, if we go beyond the limits of perturbation theory and use Schiff's eikonal approximation[4] for the analysis of scattering[5] and bremsstrahlung,[6] we obtain essentially new results, namely an orientational dependence of the yield of the bremsstrahlung photons of maximum energy on the angle at which the electrons enter the crystal.

To observe this orientational dependence, we used the Erevan accelerator, with electron energy 4.5 GeV, to investigate experimentally the yield of bremsstrahlung photons of 4.38 GeV energy. The electron beam was incident on a diamond plate parallel to the [100] axis mounted on a goniometer. The accuracy of the angle setting was ±0.04 mrad. The bremsstrahlung γ quanta were rid of the charge particles by means of two clearing magnets and were collimated within an angle 0.16 mrad. In the experiment, a paired γ spectrometer was used to measure the number of electrons and position pairs corresponding to a γ-quantum energy 4.38 GeV. The photon energy was measured accurate to 1.2%. The measurement results are shown in the figure.

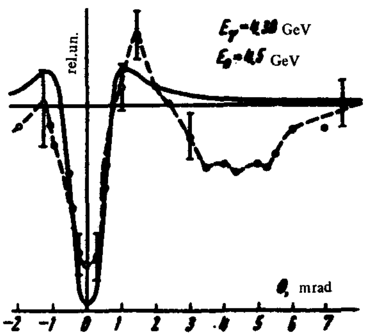
The theoretical calculations were performed with the aid of the eikonal approximation (see, e.g.,[6]). In the calculations, the interaction of the electrons with the crystal atoms was not described by perturbation theory, but the interaction with the radiation field was regarded as a perturbation. Since the initial electron moves practically parallel to a crystallographic axis, account was taken of the changes of phase only in the initial state of the electron. In addition, at large momentum transfers ($x \sim 1$) it is possible to calculate the cross section for one chain and multiply the final results by the number of atoms in the plane perpendicular to the momentum of the initial electron.

Starting from the foregoing, we obtain for the differential cross section of the bremsstrahlung of photons of maximum energy in a single crystal the expression

$$d\sigma_{\text{theor}} = d\sigma_{\text{br}}^{\text{theor.poss.}} \left\{ \frac{\pi\beta}{2NZe^2} + \frac{1 + 2\left(\frac{2Ze^2}{\beta a m}\,\psi^{-1}\ln\frac{2m}{\gamma\kappa}\right)^2}{\left[1 + 4\left(\frac{2Ze^2}{\beta a m}\,\psi^{-1}\ln\frac{2m}{\gamma\kappa}\right)^4\right]^{3/2}} \right\}. \qquad (1)$$

N is the number of atoms in the chain, κ is the reciprocal screening radius, ψ is the entrance angle, and $\ln\gamma = C = 0.577$ is the Euler constant. In the derivation of (1) we neglected the thermal vibrations of the lattice atoms.

Near a zero entrance angle $\psi \to 0$ it follows from (1)



Yield of bremsstrahlung γ quanta from a diamond crystal as a function of the electron entrance angle relative to [100]. The electron momentum lies in the (001) plane. Dashed curve—experimental, solid curve—plot of formula (1), straight line—perturbation theory.

that the yield of the bremsstrahlung photons decreases strongly.

$$d\sigma_{br\ 4}(\psi = 0) = d\sigma_{br}^{\text{theor.poss.}} \quad \frac{\pi\beta}{2NZe^2} \qquad (2)$$

The characteristic angular dimension of the minimum is determined by

$$\psi_0 = \frac{2Ze^2}{\beta a m} \ln \frac{2m}{\gamma \kappa} \quad . \qquad (3)$$

The cross section behaves like $d\sigma \sim \psi^4$ at $\psi < \psi_0$ and like $d\sigma \sim A + B/\psi^2$ at $\psi > \psi_0$. At $\psi = 1.1$ mrad there is a maximum in the cross section. With further increase of the entrance angle, $\psi \gg \psi_0$, the differential cross section for bremsstrahlung of hard photons is determined by the expression calculated by perturbation theory.

The observed effect agrees with the theoretical expression (1) within the limits of experimental error. However, the theoretical cross section is less than the experimental one at the minimum, because the theoretical analysis does not take into account the initial divergence of the electron beam, nor the thermal vibrations of the lattice atoms.

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