Coherent emission of characteristic lines on passage of charged particles through a single crystal

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A new effect is predicted—emission of coherent characteristic lines of a sample in the x-ray band on passage of charged particle through a single crystal. The possibility of observing and using this effect to obtain coherent x rays is discussed.

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1. The subject of this article is a discussion of new possibilities of obtaining coherent x rays by passing charged particles through a single crystal. Principa attention is paid to the so-called quasi-Cerenkov (QC) radiation due to the periodic inhomogeneity of the refractive index in the crystal. A new effect is noted namely the appearance of characteristic lines in the spectrum of the coherent QC radiation.

2. In connection with the problem of x-ray lasers, interest in coherent x radiation of charged particles has again increased in recent years. A promisin medium from this point of view is a single crystal, since the natural spatial periodicity can be used to select the radiation, to produce distributed feedback, etc. In high-energy physics, attention was already called to the possibility of the specific mechanism of coherent radiation in crystals—transition radiation on atomic inhomogeneities of the medium. See the review[1] and[2–4].) This radiation can be called quasi-Cerenkov, since the usual Cerenkov radiation con dition is satisfied here for bound waves in the crystal. Most frequency QC radi· ation is assumed to be negligibly small (an exception is discussed in[4]). We shall show that there exists an important mechanism that leads to an increase in the intensity of the QC radiation.

3. We consider the semiclassical field equations in a medium

$$-\frac{1}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} + \Delta \mathbf{A} = -\frac{4\pi}{c}(\mathbf{j} + \mathbf{j}_q)^{\perp}, \tag{1}$$

where $\mathbf{j}_q$ is the classical current of the passing particle, j is the quantum-mechanical of the medium current operator. In the approximation in which the dielectric susceptibility is constant we have $\mathbf{j}(\mathbf{r}, \omega) = -i\omega\kappa_\omega|(\mathbf{r})\mathbf{E}(\mathbf{r}, \omega)$, and for a crystal $\kappa_\omega(\mathbf{r}) = \kappa_\omega^0 + \Sigma_{\mathbf{K}\neq 0}\kappa_\omega(\mathbf{K})\exp(i\mathbf{K}r)$. In first-order approximation in $\kappa_\omega(\mathbf{K})$, taking the smallness of κ_ω^0 into account, we obtain for the QC radiation

$$\mathbf{A}_1(\mathbf{k}) = 2icq \sum_{\mathbf{K}\neq 0}\kappa_\omega(\mathbf{K})\frac{\omega \mathbf{v}^{\perp} + \tilde{c}^2\mathbf{K}^{\perp}}{\omega^2 - \tilde{c}^2(\mathbf{k}-\mathbf{K})^2}\int \delta(\omega - \mathbf{kv} + \mathbf{Kv} - \kappa\mathbf{v})\,\chi_V(\vec{\kappa})\,d\vec{\kappa} \tag{2}$$

($\tilde{c} = c/\sqrt{\epsilon}$, χ_V is the projector on the sample volume, and $\omega = \tilde{c}k$). This radiation is a consequence of the resonance between the induced current and the oscilla-

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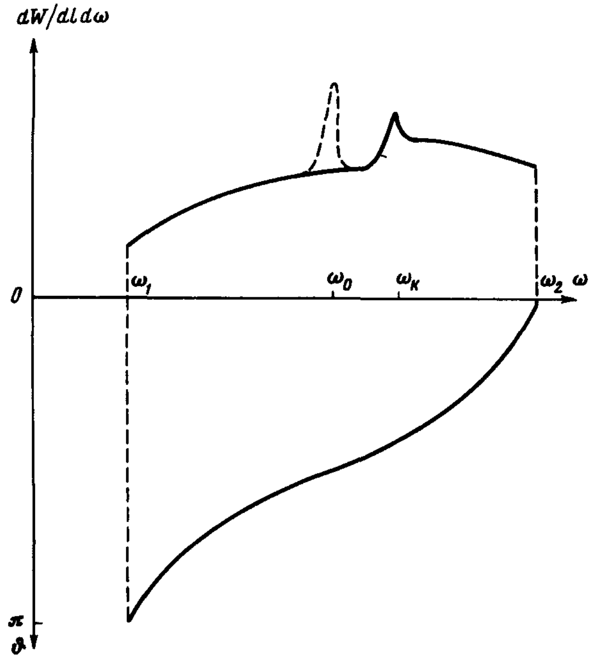
rs of the field of the homogeneous medium with $\kappa_\omega(\mathbf{r}) = \kappa^0_\omega$. "Pure" QC radiation in an unbounded medium corresponds to the limit $\chi_V \to (2\pi)^3\delta(\kappa)$. It is characterized by a single-valued dependence of the radiation angle θ between and $\mathbf{v}$ on the frequency: $\cos\theta = [1 + \mathbf{K}\cdot\mathbf{v})/\omega]/\tilde{\beta}$ ($\tilde{\beta} = \mathbf{v}/\tilde{c}$) by virtue of the resonance condition $\omega = \tilde{c}k = (\mathbf{k} - \mathbf{K})\cdot\mathbf{v}$. (This dependence is represented by the lower curve of the figure.) The radiation corresponding to fixed $\mathbf{K}$ has a frequency and

$$\omega_1 = |\mathbf{K}\mathbf{v}| / (1 + \tilde{\beta}) < \omega < \omega_2 = |\mathbf{K}\mathbf{v}| / (1 + \tilde{\beta}) ,$$

ith the higher-frequency part directed forward. For an aluminum crystal at n electron energy 24.5 keV and $\mathbf{v} \parallel [111]$ we have $\omega_1 = 1.9$ and $\omega_2 = 3.4$ (10^{18} rad/ec). The distribution of the energy over the spectrum, with allowance for the requency dependence of $\kappa_\omega(\mathbf{K})$ on the contribution made only by the K-jump of e absorption is shown in the figure (solid curve). If we take into account in (2) nly the contribution from $\mathbf{K}_0 = 2\pi[[111]]$, the total radiation energy in the entire pectrum amounts to $dW/dl = 0.95 \times 10^{-3}$ quanta/cm, the contribution of the K-ump being $\approx 10\%$. The latter is characterized by a logarithmic intensity spike ith which, however, no essential localization of the energy is connected.



The spatial distribution of the intensity over the solid angle is determined y the expression

$$\frac{dW}{d\Omega} = \frac{\omega l}{2} \frac{dW}{dl\, d\omega} \frac{\tilde{\beta}}{1 - \tilde{\beta}\cos\theta} . \quad (3)$$

t relativistic velocities, the denominator of (3) at $\theta = 0°$, that is, for forward adiation, is of the order of 10^{-4}—10^{-5}. By a judicious choice of the crystal orientation it is always possible to cause the frequency corresponding to the characteristic line of the susceptibility $\kappa_\omega(\mathbf{K})$ to be emitted in this convenient direction.

4. If the particle moves along a channeling direction, then the equation $(\mathbf{K}\cdot\mathbf{v}) = 0$ has an infinite set of solutions $\mathbf{K}_n$ that make up a plane in reciprocal space. For all the points of the planes in the form $\mathbf{K}=\mathbf{K}_0+\mathbf{K}_n$, the terms of the sum in (2), which describes the radiation of a classical charge, differ only by a factor in front of the integral, that is, they correspond to identical waves. The sum converges because of the cutoff role of $\kappa_\omega(\mathbf{K})$, which contains, in particular, an atomic factor (in the case of the electronic susceptibility). The role of the structure factor reduces to annihilation of the contributions of certain $\mathbf{K}_0+\mathbf{K}_n$. In the considered example with aluminum, for the plane $\mathbf{K}=2\pi\{[[\bar{1}\bar{1}\bar{1}]] + [[lm(\overline{l+m})]]\}$, the structure factor is equal to -1 for even l and m and to 0 in the opposite case. The effect due to summation of the contributions of all the points of the plane amounts to approximately one order in the amplitude, i.e., almost two orders in intensity.

5. The physical mechanism for the excitation of the characteristic lines in the QC radiation spectrum consists in excitation of the nearest atoms by the moving particle and simultaneous QC radiation from the excited atoms: this effect will be called self-pumping.[1)]

Second-order perturbation theory yields for the average quantum current of the medium an expression that depends quadratically on the field of the exciting current; for a single particle, after summation over all the transitions with emission of the quadrupole line $K_{\beta 5}$, we obtain for the case of channeling the spectral distribution

$$\frac{dW}{dl\,d\omega} \sim 10^5 \frac{\chi e^{10}}{\hbar (mc^2)^3 \Omega^2 \omega_0} \left(\frac{cK_0 |Z(K_0)|}{vk} \right) z_K z_M z_{KM} \frac{\omega}{(\omega-\omega_0)^2+\gamma^2},$$

where z_K, z_M, and z_{KM} are oscillative strengths of K and M absorption and of the dipole $K_{\beta 1}$ transition, and χ is the relative intensity of the $K_{\beta 5}$ and $K_{\beta 1}$ lines. If γ is identified in this expression with the width of the spontaneous-emission line, then the intensity at the maximum amounts to $10^{-2}-1$, and for copper is amounts to 10^{-1} of the spectral density of the continuous QC spectrum.

6. For relativistic particles, the density of the characteristic QC radiation due to localization near $\theta = 0°$ can, according to (3), be sufficiently high. Thus, on a path $l = 10\ \mu$, for a relativistic electron in a copper sample, at an emission angle $\theta = 1°$ of the characteristic line the self-pumping effect, causes its energy $\sim 10^{-8}$ quantum to be localized in a solid angle $\Omega \sim 10^{-6}$ sr. This is larger by two orders of magnitude than the typical densities of the spontaneous emission excited by electrons.[5]

7. The characteristic QC radiation due to self-pumping is not connected with a high level of spontaneous background; its intensity depends nonlinearly on the flux density of the charged particles. It is interesting that an experimental observation of a similar relation is reported in[6]. In our opinion, experiments of this type should be continued.

8. The foregoing estimates show that we are dealing with a perfectly observable effect. The intensity of the characteristic radiation can be greatly

ıcreased (as shown by estimates, by at least two orders of magnitude) by imultaneously using the effects of particle channeling and anomalous transıission of x rays. We note finally that the characteristic Cerenkov radiation ue to the self-pumping effect can be of definite interest also in the optical and.

)Estimates show that the use of external (for example, "optical") pumping is much less effective.

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