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The Borrmann effect in parametric X-radiation under asymmetric reflection conditions

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Abstract

Parametric X-radiation (PXR) of a relativistic electron traversing a single crystal plate is considered in Laue geometry. The expressions describing spectral–angular distributions of PXR formed on the atomic planes situated under arbitrary angle δ to surface of the plate (asymmetric reflection) obtained on basis of two-wave approximation of dynamic diffraction theory are used for definition of the conditions of the most pronounced manifestation of the Borrmann effect (optimal value of angle δ) are clarified. This effect leads to considerable increase of the intensity of the quasi-monochromatic tuning source of coherent X-radiation built on basis of PXR.

Keywords: Relativistic electron; Parametric X-radiation; Diffracted transition radiation; Single crystal

1. Introduction

The effect of anomalous photoabsorption low is one of the dynamic effects in scattering of free X-rays in a crystal. For the first time this effect has been experimentally found out by Borrmann [1] in his experiments on free X-rays dispersion in a crystal. The physics of this effect consists in formation of a standing wave by incident and scattered waves, whose antinodes are located in the middle of the space between the neighbouring nuclear planes, where the density of atomic electrons (and the photoabsorption accordingly) are minimal. In these conditions two-waves are formed in the crystal, one of which is absorbed abnormally strongly and another abnormally weakly. The linear absorption factor for both waves looks as follows [2]:

$$\mu = \mu_0\left(1 \pm C^{(s)}\frac{\chi''_g}{\chi''_0}\right), \qquad (1)$$

where sign "+" corresponds to the abnormally strong absorption, and "−" to abnormally weak absorption, $\chi''_{\vec g}$ and χ''_0 are imaginary parts of factors in expansion of the dielectric susceptibility in the Fourier series by a reciprocal lattice vectors $\chi = \sum_{\vec g}(\chi'_{\vec g} + i\chi''_{\vec g})e^{i\vec g\vec r}$, $C^{(s)}$ is a polarization factor. For σ-polarization $C^{(1)} = 1$, for π-polarization $C^{(2)} = |\cos 2\theta_B|$, θ_B is the angle between an incident X-ray beam and a set of crystal planes (Bragg angle). It is obvious from the formula 1, that Borrmann effect is more brightly manifested for σ polarization. The necessary condition of observation of this effect is $\chi''_{\vec g} \cdot C^{(s)}/\chi''_0 \approx 1$.

The actual question arises whether a similar effect exists in parametric X-ray radiation (PXR) [3–5] realized in pseudo-photons Bragg diffraction process of Coulomb fields of the fast particle moving in a crystal. Influence of Borrmann effect on the characteristics of PXR was considered in [7,8]. Earlier it was shown in [6] that an additional contribution (besides PXR) to output from a thick absorbing crystal target by transition X-radiation generated by fast particle on enter target surface and diffracted on the same system of atomic planes can considerably increase

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due to the Borrmann effect for free photons in the crystal. In the works [7–9] Borrmann effect was predicted for pseudo-photon field of radiating particle in Bragg and Laue geometries. However in [6–9] PXR and diffracted transitive radiation (DTR) were considered within the scheme of symmetric reflection and Borrmann effect was considered in the extreme case of semi-infinite crystal which in the real experiment could lead to a decrease of this effect due to multiple scattering of the radiating particle into the target. Under symmetric reflection the crystal target surface is situated in parallel with the system of diffracting atomic planes in case of scattering in Bragg geometry ($\delta = 0$) and perpendicular to them in case of geometry of Laue ($\delta = \pi/2$).

It was shown in the works [10,11] that spectral–angular distribution of PXR and DTR considerably depends on the angle δ. In the case of semi-infinite crystal within Bragg geometry, Borrmann effect manifestation was considered in [12].

In the present work the coherent X-radiation by relativistic electron, traversing a monocrystalline plate is considered within Laue geometry of scattering. The analytical expressions for spectral–angular distributions PXR, DTR and for the term describing the interference of these two radiation mechanisms are obtained in the general case of asymmetric reflection, namely with taking to the account orientation of system of diffracting atomic planes in the crystal to the external surface of the plate (angle δ). As a result the conditions of the brightest manifestation of Borrmann effect were clarified. In particular, it was shown that on the one hand under increase of the asymmetry by means of angle δ increase one can decrease the path of relativistic electron in the plate (condition when the effect of electron multiply scattering can be neglected) and at the same time increase the path of PXR (condition when Borrmann effect manifests itself). On the other hand under increase of the asymmetry by means of angle δ decrease, this effect manifests itself weaker but leads not only to a considerable increase of radiation intensity (which is obvious due to decrease of absorption) but also to spectral line spreading, which is nontrivial.

This result can be used under construction of tuning quasi-monochromatic X-ray source based on the PXR mechanism of the radiation generated by relativistic electrons in oriented monocrystalline target.

2. Anomalous photoabsorption effect in PXR

In the work [13] the expressions describing spectral–angular distributions of PXR of relativistic electron traversing a monocrystalline plate are obtained on basis of two-wave approximation of dynamic diffraction theory within Laue geometry of scattering (see Fig. 1) for asymmetric scattering (arbitrary angle δ) with taking into account the radiation absorption in the crystal substance:

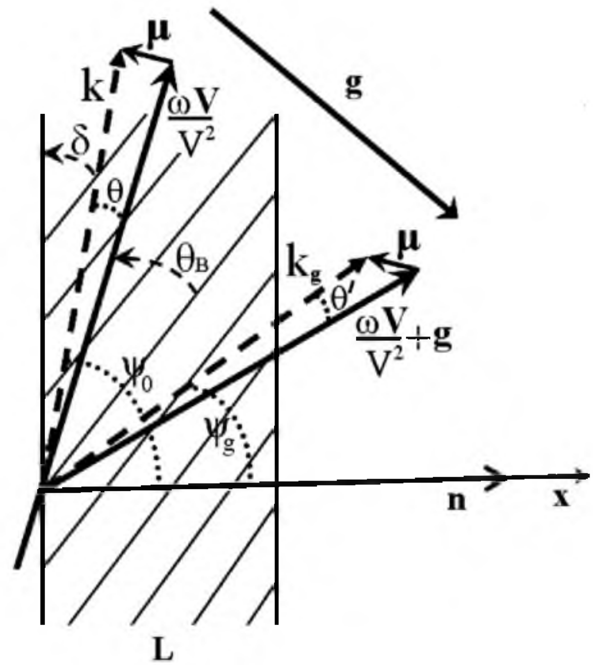

Fig. 1. The radiation process geometry. θ' is radiation angle, θ_B is Bragg angle (the angle between electron velocity V and diffracting atomic planes), δ is the angle between the plate surface and the considered atomic planes.

$$\omega\frac{d^2N_{PXR}^{(s)}}{d\omega d\Omega}=\frac{e^2}{4\pi^2}\frac{\theta^2 {P^{(s)}}^2}{(\theta^2+\gamma^{-2}-\chi_0')^2}\left|\frac{1}{K^{(s)}}\frac{\xi^{(s)}(\omega)-\frac{i\rho^{(s)}(1-\varepsilon)}{2}-K^{(s)}}{\sigma^{(s)}-\frac{i\rho^{(s)}(1+\varepsilon)}{2\varepsilon}+\frac{\xi^{(s)}(\omega)-K^{(s)}}{\varepsilon}}\left(1-e^{-ib^{(s)}\left(\sigma^{(s)}-\frac{i\rho^{(s)}(1+\varepsilon)}{2\varepsilon}+\frac{\xi^{(s)}(\omega)-K^{(s)}}{\varepsilon}\right)}\right)\right|^2, \quad (2)$$

where ${K^{(s)}}^*$ is expression complex conjugate to $K^{(s)}$.

To analyze the influence of Borrmann effect on the PXR spectral–angular characteristics in general asymmetric case let us represent the expression 2 in the following convenient view:

$$\omega\frac{d^2N_{PXR}^{(s)}}{d\omega d\Omega}=\frac{e^2}{4\pi^2}\frac{{P^{(s)}}^2}{|\chi_0'|}F_{PXR}^{(s)},$$

$$F_{PXR}^{(s)}=\frac{\frac{\theta^2}{|\chi_0'|}}{\left(\frac{\theta^2}{|\chi_0'|}+\frac{1}{\gamma^2|\chi_0'|}+1\right)^2}\left|\frac{1}{K^{(s)}}\frac{\xi^{(s)}(\omega)-\frac{i\rho^{(s)}(1-\varepsilon)}{2}-K^{(s)}}{\sigma^{(s)}-\frac{i\rho^{(s)}(1+\varepsilon)}{2\varepsilon}+\frac{\xi^{(s)}(\omega)-K^{(s)}}{\varepsilon}}\times\left(1-e^{-ib^{(s)}\left(\sigma^{(s)}-\frac{i\rho^{(s)}(1+\varepsilon)}{2\varepsilon}+\frac{\xi^{(s)}(\omega)-K^{(s)}}{\varepsilon}\right)}\right)\right|^2 \quad (3)$$

Let us consider the possibility of Borrmann effect manifestation for different orientations of the plate surface to the set of parallel diffracted atomic planes defined by parameter ε. While doing this, we will suppose the angle (θ_B) between electron velocity and reflecting planes and also the electron path length in crystal plate (L/γ_0) to be fixed. Fig. 2 shows three different orientations of the crystal plate surface relatively to the set diffracted atomic plane for fixed

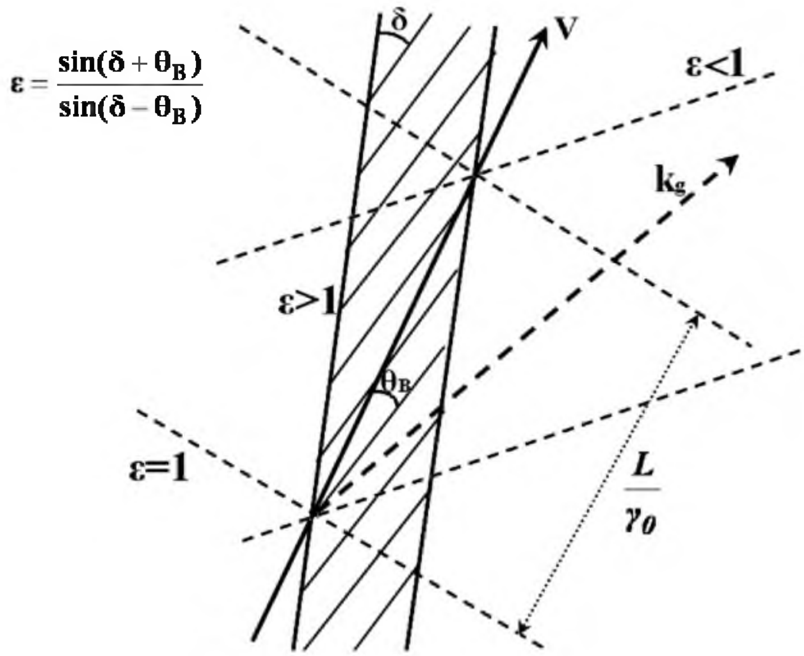

Fig. 2. Scheme of symmetric ($\varepsilon = 1$) and asymmetric ($\varepsilon > 1$, $\varepsilon < 1$) reflection of relativistic electron Coulomb field.

angle θ_{B} and electron path length (L/γ_0). To hold such conditions the thickness of the plate L must be changed depending on parameter$\varepsilon = \varepsilon(\theta_{\mathrm{B}}, \delta)$. As the parameter ε increases, the plate thickness will decrease and the path length of photons in the crystal will decrease accordingly.

In Fig. 3(a) the curves plotted by formula 3 are presented, demonstrating the manifestation of Bormann effect in a crystal of limited thickness for given value of asymmetric coefficient ε. When the parameter $\kappa^{(s)} = \frac{\chi''_g C^{(s)}}{\chi''_0}$ tends to unity, the manifestation of this effect in PXR becomes rather substantial (when $\kappa^{(s)} = 0$ Borrman effect is neglected, and when $\kappa^{(s)} = 1$ it is maximal).

It is necessary to remind that parameter $\kappa^{(s)}$ depends on the choice of set of parallel diffracting atomic planes of the crystal, frequency and polarization of the radiation. For σ-polarization ($C^{(1)} = 1$) this effect manifests itself more brightly than for π-polarization ($C^{(2)} = \cos 2\theta_{\mathrm{B}}$).

Let us point out, that in real experiment it is impossible to find the conditions when $\kappa^{(s)}$ would be equal to unity. The maximum possible value of this parameter is $\kappa^{(s)} \approx 0.9$.

The curves presented in Fig. 3(b) are analogous to the one presented in Fig. 3(a) but were calculated for other (more) value of asymmetry coefficient ε. One can see that in this case Borrmann effect will manifest itself weaker because for this case the path length of PXR photon in the plate becomes less and spectral amplitude becomes bigger. With all this going on the width of PXR spectrum grows because in 2 the real part of the fraction denominator $Re\left[\sigma^{(s)} - \frac{\mathrm{i}\rho^{(s)}(1+\varepsilon)}{2\varepsilon} + \frac{\xi^{(s)}(\omega) - K^{(s)}}{\varepsilon}\right]$ changes weaker depending on ω when value of ε is bigger.

The solution of equation

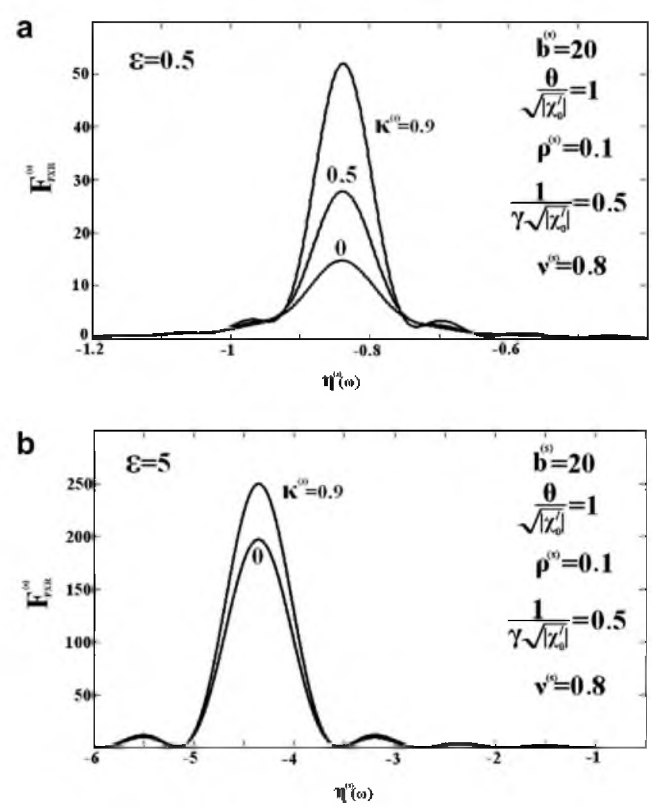

Fig. 3. The influence of asymmetry ε on manifestation degree of Borrmann effect in PXR spectral–angular density in the crystal of finite thickness: (a) asymmetry coefficient $\varepsilon = 0.5$; (b) asymmetry coefficient $\varepsilon = 5$.

$$Re\left[\sigma^{(s)} - \frac{\mathrm{i}\rho^{(s)}(1+\varepsilon)}{2\varepsilon} + \frac{\xi^{(s)}(\omega) - K^{(s)}}{\varepsilon}\right] = 0 \qquad (4)$$

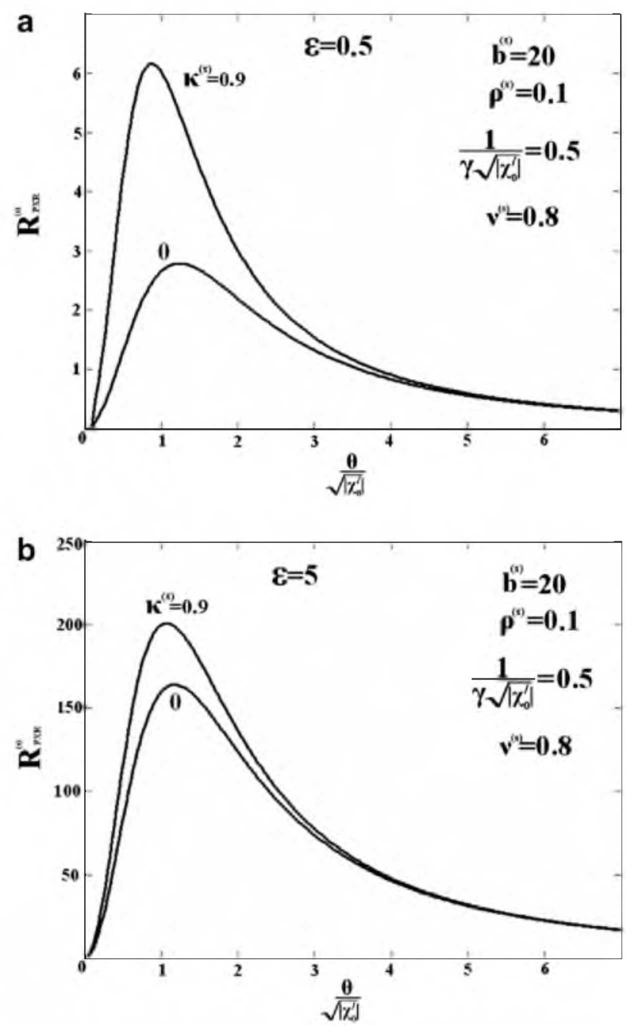

Fig. 4. The influence of asymmetry ε on manifestation degree of Borrmann effect in PXR angular density in the crystal of finite thickness: (a) asymmetry coefficient $\varepsilon = 0.5$; (b) asymmetry coefficient $\varepsilon = 5$.

defines the frequency in whose vicinity are concentrated spectrum of photons of PXR radiated at fixed observation angle.

In conclusion, let us consider the influence of Borrmann effect on the angular density of PXR. For this purpose we will integrate the expression 3 over the frequency function $\eta^{(s)}(\omega)$

$$\frac{dN^{(s)}_{\mathrm{PXR}}}{d\Omega} = \frac{e^2 \nu^{(s)} P^{(s)^2}}{8\pi^2 \sin^2\theta_B} R^{(s)}_{\mathrm{PXR}},$$
$$R^{(s)}_{\mathrm{PXR}} = \int_{-\infty}^{+\infty} F^{(s)}_{\mathrm{PXR}}\, d\eta^{(s)}(\omega). \qquad (5)$$

The curves of $R^{(s)}_{\mathrm{PXR}}$ presented in Fig. 4(a) and (b) demonstrate Borrmann effect influence to angular density of PXR for two different asymmetry coefficients under the same condition as in Fig. 3(a) and (b) accordingly.

3. Conclusion

In the present work, the analytical expressions of spectral–angular distribution of PXR and DTR of relativistic electron traversing the single crystal plate of finite thickness are obtained based on two-wave approximation of dynamic diffraction theory in Laue scattering geometry for general case of asymmetrical reflection. The expression obtained contains the angle between crystal plate surface and diffracting atomic plane of the crystal (angle δ) and allows to research the manifestation degree of dynamic Borrmann effect in PXR depending on angle δ. In this work it is shown that by changing the reflection asymmetry coefficient the condition can be created, when electron scattering effect will be neglected and the path of the PXR photons in the crystal exceeds the absorption length which will lead to bright manifestation of Borrmann effect in PXR and permit its disclosure. This effect allows to essentially increase the intensity of tuning quasimonocromatic X-ray source based on PXR mechanism.

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