GENERATION OF POLARIZED GAMMA-QUANTA BY RELATIVISTIC ELECTRONS INTERACTED WITH AN ATOMIC STRING IN A CRYSTAL

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Introduction

Coherent bremsstrahlung of relativistic electrons in an aligned crystal is one of the most effective methods of high energy quasimonochromatic linear polarized gamma-quantum production [1]. It is well known that the intensity of coherent bremsstrahlung increases when an orientation angle ψ between radiating particle velocity and the axis of an atomic string of a crystal decreases. But in the region of angle magnitude $\psi \sim \psi_c$ (ψ_c is the crytical channeling angle) the strong azimutal coherent scattering of electrons on atomic strings arises and in a consequence of which the correlations between consecutive collisions of the electron with different atomic strings are destroyed.

The investigations of the intensity and polarization of the coherent radiation on condition under consideration are very interesting with the view of the exposure of new possibilities of polarized quantum production.

This work is devoted to theoretical research of two coherent mechanisms of linear polarized photon emission by relativostic electrons interacting with the single atomic string of a crystal. The first of them allows one to produce small energy quanta using the scattering of the electron in the average string's potential. The Second of them baseds on the discrete structure of an atomic string and allows one to produce quanta with energy $\omega \sim \varepsilon$ (ε is the energy of radiating electron).

Generation of linear polarized γ-quanta in the process of noncorrelated collisions of relativistic electrons with atomic strings in a crystal

Let's consider the emission of the flux of relativistic electrons moving in a crystal at a small angle ψ to one of the main crystallographic axis $\vec{e}_z$. On condition under consideration, when the particle's collisions with different atomic strings are accidental ($\psi \geq \psi_c$, the direction of the vector $\vec{\psi} - \vec{e}_t \cdot \vec{e}_z \vec{\psi}$ does not coincide with the main crystallographic directions in the plane perpendicular to the axis $\vec{e}_z$, $\vec{V}$ is the electron velocity, ψ_c is the critical channeling angle) the polarization and spectral-angular distribution of the radiation intensity are described by the polarization matrix

$$\frac{dI_{jk}}{d\omega dO} = n_0 d\psi \int db \frac{dE_{jc}}{d\omega dO}, \tag{1}$$

where n_0 is the atomic density of the crystal, d is the distance between atoms in the string, integration in (1) is performed all over impact parameters b, $\frac{dE_{jk}}{d\omega dO}$ is the polarization matrix of the electron emission on a separate string:

$$\frac{dE_{jk}}{d\omega dO} = \frac{e^2\omega^2}{4\pi^2} \left\langle \int dt_1 dt_2 V_{1j} V_{2k} e^{i\omega(t_1 - t_2 - \vec{n}(\vec{r}_1 - \vec{r}))_2} \right\rangle, \tag{2}$$

where $\vec{r}(t)$ is the particle's trajectory, brackets $\langle\ \rangle$ mean averaging all over the electron trajectories.

The result of calculations which follows from (1)-(2) within the framework of dipole approximation has the form

$$\frac{dI_{jk}}{d\omega d^2\theta}=\frac{4Z^2e^6n_0}{\pi^2m^2\gamma^2}\frac{1}{(\gamma^{-2}+(\vec{\psi}-\vec{\theta})^2)^2}\int\frac{d^2K_\perp}{(K_\perp^2+R^{-2})^2}\cdot$$
$$\tau_j\tau_k\cdot\left\{\frac{2\pi}{d}e^{-K_\perp^2U_T^2}\delta\left(\frac{\omega}{2}(\gamma^{-2}+(\vec{\psi}-\vec{\theta})^2)-\vec{K}_\perp\vec{\psi}\right)+1-e^{-K_\perp^2U_T^2}\right\} \qquad (3)$$

$$\tau_1=K_y-2\frac{\psi_y-o_y}{\gamma^{-2}+(\vec{\psi}-\vec{o})^2}(\vec{\psi}-\vec{o},\vec{K}_\perp),$$

$$\tau_1=K_x-2\frac{\psi_x-o_x}{\gamma^{-2}+(\vec{\psi}-\vec{o})^2}(\vec{\psi}-\vec{o},\vec{K}_\perp),$$

where Z is the atomic number, electron energy $\varepsilon=m\gamma$, values $\vec{\psi}$ and $\vec{\theta}$ are determined by the formulas

$$\vec{n}=\vec{e}_z\left(1-\frac{1}{2}\theta^2\right)+\vec{\theta},\quad \vec{e}_z\vec{\theta}=0,$$
$$\qquad (4)$$
$$\vec{v}=\vec{e}_z\left(1-\frac{1}{2}\gamma^{-2}-\frac{1}{2}\psi^2\right)+\vec{\psi},\quad \vec{e}_z\vec{\psi}=0.$$

The term in (5) which is proportional to δ-function describes the contribution of the coherent part of the electron scattering to the emission yield. The term which is proportional to $1-e^{-K_\perp^2u_1^2}$ corresponds to contribution of the incoherent scattering.

The result of the integration in (3) over $d^2K_\perp$ has the following form

$$\frac{dI_{jK}}{d\omega d^2O}=\frac{8Z^2e^6n_0}{m^2\gamma^2}\frac{1}{\left(\gamma^{-2}+(\vec{\psi}-\vec{o})^2\right)^2}\left\{\frac{R}{d\psi}\frac{1}{\sqrt{1+K_0^2R^2}}A_{jK}^{coh}+\frac{\ln(mu)}{2\pi}A_{jK}^{inc}\right\},$$
$$K_0=\frac{\omega}{2\psi}\left(\gamma^{-1}+(\vec{\psi}-\vec{o})^2\right),$$
$$A_{11}^{coh}=\left(1-\frac{2(\psi_y-o_y)}{\gamma^{-2}+(\vec{\psi}-\vec{o})^2}\right)^2\cdot\left(F_1-\frac{1}{2}F_2\right)+\frac{1}{2}\frac{K_0^2R^2}{1+K_0^2R^2}\frac{4(\psi_x-o_x)^2(\psi_y-o_y)^2}{\left(\gamma^{-2}+(\vec{\psi}-\vec{o})^2\right)^2}F_2,$$
$$A_{22}^{coh}=\frac{4(\psi_x-o_x)^2(\psi_y-o_y)^2}{\left(\gamma^{-2}+(\vec{\psi}-\vec{o})^2\right)^2}\left(F_1-\frac{1}{2}F_2\right)+\frac{1}{2}\frac{K_0^2R^2}{1+K_0^2R^2}\left(1-\frac{2(\psi_x-o_x)^2}{\gamma^{-2}+(\vec{\psi}-\vec{o})^2}\right)^2\cdot F_2,$$
$$F_2=1-\Phi\left(\frac{U_T}{R}\sqrt{1+K_0^2R^2}\right),$$

$$A_{11}^{inc} = 1 - \frac{4\gamma^{-2}(\psi_y - o_y)^2}{\left(\gamma^{-2} + (\vec{\psi} - \vec{o})^2\right)^2}, \quad A_{22}^{inc} = 1 - \frac{4\gamma^{-2}(\psi_x - o_x)^2}{\left(\gamma^{-2} + (\vec{\psi} - \vec{o})^2\right)^2}. \qquad (5)$$

The expression obtained allows one to research the influence of the crystal temperature, the photon emitted collimation, the contribution of incoherent scattering on the spectral-angular distribution and the polarization degree of the radiation.

Let's consider first of all the influence of the photon collimation on the spectral distribution and polarization degree of the radiation registered by a detector with an angular size θ_d located along the electron beam axis.

In Fig.1 the spectral distribution $\frac{dI}{d\omega}$ and linear polarization degree $\xi_j(\omega)$ as a function of the photon energy and angular size of the detector are represented. The culculations were performed without taking into account the influence of thermal vibrations of atoms and incoherent scattering of the electron on the coherent emission process. On accordance with curves in Fig.1 emission spectrum concentrates in the region $\omega \leq \omega_0 = 2\gamma^2\psi / R$. This ineguality means exceeding the coherent length $l_{coh} = \frac{2\gamma^2}{\omega}$ over the length of the electron interaction with a string $\frac{R}{\psi}$. For this reason in the case ot $l_{coh} \succ \frac{R}{\psi}$ the maximum number of string's atoms $n_{max} \approx \frac{R}{d\psi}$ makes the coherent contribution to the emission yield (in the case of dipole emission).

The mechanism of the linear polarization origin is explained by the behavior of the function $\xi_j(\omega)$. The direction and the magnitude of the polarization are determined by the average electron acceleration on the coherent length l_{coh}. In the region of small frequancies $\omega \prec \omega_0$ ($l_{coh} \succ \frac{R}{\psi}$) the effective averaging of the sine-variable acceleration component parallel to the incident plane takes place. For this reason in the frequancy region mentioned the polarization properties of radiation are determined by the sine-invariable acceleration component perpendicular to the incident plane in accord with the curves in Fig.1. In the case of $l_{coh} \prec\prec \frac{R}{\psi}$ average acceleration component parallel and perpendicular to the a incident plane have the same order of magnitude. Therefore the polarization degree decreases when a frequancy ω inereases.

The curves in Fig.2 demonstrate the new effect. In is seen from Fig.2 that the direction of polarization changes when the photon energy incneases. To obtaine this effect one can take into account the influence of termal vibrations of string's atoms on the average string potential. One can explaine this effect by means of following reasoning. The relative contribution of small impact parameters of electron collisions with a string increases together with the photon energy ω. Due to termal vibrations of atoms the gradient of the average string's potential has a small magntude clouse to zero in the region of $r_\perp \prec u_T$. It is easy to show that on condition considered (electron trajectory like straight line) the electron acceleration component parallel to the incident plane makes the main contribution to coherent radiation yield for the small impact parameters $b \leq u_T$. This circumstance is the cause of the effect discussed.

The result (5) allows*one to research the influence of nonaxial collimation of the photons emitfed upon the polarization properties. The spectral-angular and polarization characteristics as a function of the parameter $\gamma(\psi_x$-$o_x)$ which determines the deviation of the collimator from the electron beam axis are shown in Fig.3. The curves in Fig.3. demonstrate possibility to inerease essentially the polarization degree by means of nonaxial collimation. But the intensity of the photon flux emitted decreases on condition under consideration.

Generation of linear polarized γ-quanta by means of coherent bremsstrahlung type B on condition of nonaxial collimation

The method considered above allows one to produce the linear polarized γ-quanta with a small energy $\omega \ll \varepsilon$ (ε is the electron energy). To produce the hard γ-quanta with energy $\omega \approx \varepsilon$ one can use the well known coherent bremsstrahlung type B mechanism [2]. Experimental investigations [3] have pruved the high efficiency of this method to produce quasimonochroma-tic γ-quanta in the region $\omega \approx \varepsilon$. But the polarization degree obtained in this experiment was not very large. This circumstance is conditioned by the high level of symmetry of the crystal potential distribution in the plane perpendicular to atomic strings which are used for the generation of γ-quanta.

In order to increase the polarization degree we propose to employ the coherent bremsstrahlung type B in combination with nonaxial collimation of photons emitted. We will perform the calculations on the base of formula (1) where the value $\frac{dE_{jk}}{d\omega dO}$ is determined by the general quasiclassical Baier-Katkov formula [4]. Performing the calculation as it is described above we find the following expression for the polarization matrix

$$\frac{dE_{jk}}{d\omega dO} = \frac{Z^2 e^6 n_0}{\pi^2 \varepsilon^2} \cdot \int \frac{d^3K}{(K^2 + R^{-2})^2} G_{jk} \left\{ \frac{2\pi}{d} \sum_g \delta(K_z - g) e^{-K^2 U_T^2} + 1 - e^{-K^2 U_T^2} \right\} \delta\left(\omega'(1 - \vec{n}\vec{V}) - \vec{K}\vec{V}\right)$$

$$G_{jk} = \frac{\varepsilon'}{\varepsilon} a_j a_k + \frac{\omega^2}{4\varepsilon^2} \frac{(\vec{K} - \vec{V} \cdot \vec{K}\vec{V})^2}{(1 - \vec{n}\vec{V})^2} \delta_{jk},$$

$$\vec{a} = \frac{\vec{K} - \vec{V} \cdot \vec{K}\vec{V}}{1 - \vec{n}\vec{V}} + \frac{\vec{V}}{(1 - \vec{n}\vec{V})^2} (\vec{n}\vec{K} - \vec{n}\vec{V} \cdot \vec{K}\vec{V}), \qquad (6)$$

where $\varepsilon' = \varepsilon - \omega$, $\varepsilon'\omega' = \varepsilon\omega$, $g = \frac{2\pi}{d} n$, $n = 0, \pm 1, \ldots$. The term in (6) associated with g=0 describes the coherent bremsstrahlung witch has been considered above. The terms with $g \neq 0$ coresponds to coherent bremsstrahlung type B.

The final expressions for the spectrum and polarization degree of well - collimated radiation have the form

$$\frac{dE}{dtd\omega} = E_0 F(x, y), \qquad E_0 = \frac{4Z^2 e^6 n_0}{m^2},$$

$$F = \frac{1}{(1 + y^2)^2} \left((1 - x) \frac{1 + y^4}{(1 + y^2)^2} + \frac{1}{2} x^2 \right) \left(\gamma^2 O_d^2 f^{inc} + f^{coh} \right),$$

$$f^{inc} \approx \ln\left(\frac{m^2 + K_0^2}{R^{-2} + K_0^2} \right) - \frac{m^2}{m^2 + K_0^2} + e^{-K_0^2 U_T^2} - \left(1 + K_0^2 U_T^2\right) E_1\left(\frac{U_T^2}{R^2} + K_0^2 U_T^2 \right),$$

$$f^{coh} \approx 2\alpha \left(E_1\left(\frac{U_T^2}{R^2} + g^2 U_T^2 \right) - 1 \right) \frac{1 - x}{x} artg \sqrt{\frac{\gamma^2 O_d^2 - Z_{(-)}}{Z_{(+)} - \gamma^2 O_d^2}} \, \sigma(x - x_{(+)}) \sigma(x_{(-)} - x), \qquad (7)$$

$$\xi_j = \frac{2y^2}{1 + y^4 + \frac{x^2}{2(1-x)}(1+y^2)^2}, \qquad x_{(\pm)} = \alpha\left(1 + \alpha + (y \pm \gamma O_d)^2\right)^{-1},$$

$$Z_{(\pm)} = \left(y \pm \sqrt{\alpha \frac{1-x}{x} - 1}\right)^2,$$

where $\alpha = 2\gamma g / m$, $y = \gamma|\psi_x - O_x| \succ \gamma O_d$, $x = \omega / \varepsilon$, $K_0 = \frac{mx}{2\gamma(1-x)}(1+y^2)$.

The result (7) takes into account the coherent and incoherent radiation. It is valid provided $\gamma O_d \prec\prec 1$ (O_d is the detector's angular size).

On condition of a strong collimation ($\gamma O_d \prec\prec 1$) the spectral dependence of the polarization degree is determined by the value $y = \gamma(\psi - O_x)$ only. The formula for $\xi_j(x)$ shows a possibility to obtaine the essential polarization in the region of $y \geq 0{,}5$. The position of spectral peak is determined by the parameter α. The radiation spectral distribution is illastrated in Fig.4 for different magnitudes of the parameters y, and α.

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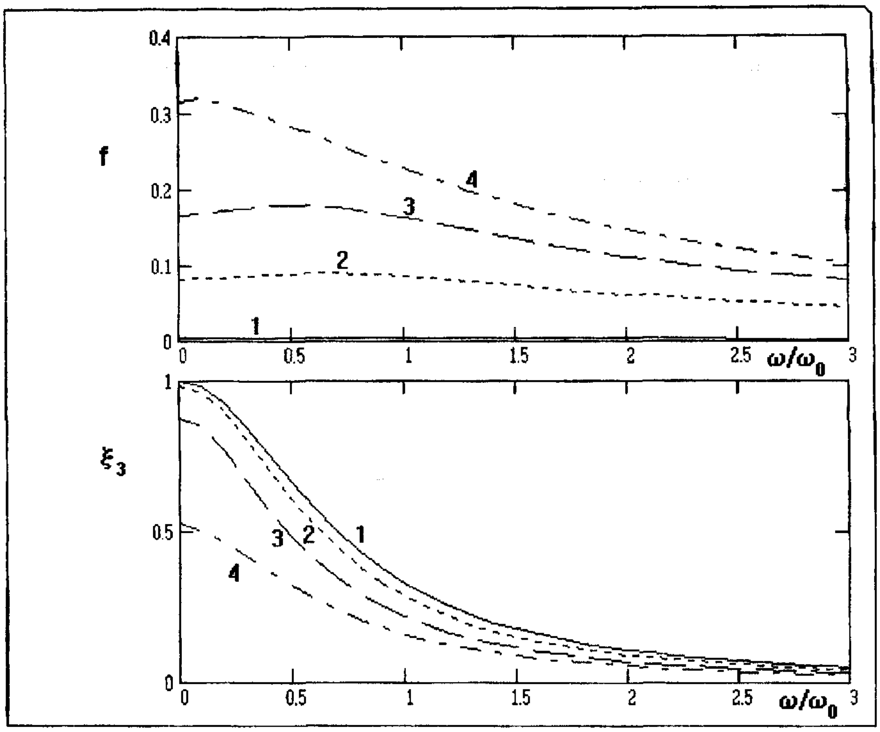

Fig.1. The radiation spectrum $\frac{dI}{d\omega} = \frac{\gamma\pi Z^2 e^6 n_0}{m^2} f$ and the linear polarization degree $\xi_3 = \left(\frac{dI_{11}}{d\omega} - \frac{dI_{22}}{d\omega}\right)\left(\frac{dI}{d\omega}\right)^{-1}$ as functions of the emitted photon energy ω and the detector's angular size O_d: 1-γO_d=0,1; 2-γO_d=0,5; 3-γO_d=1; 4-γO_d=5; $\omega_o=2\gamma^2\psi R^{-1}$.

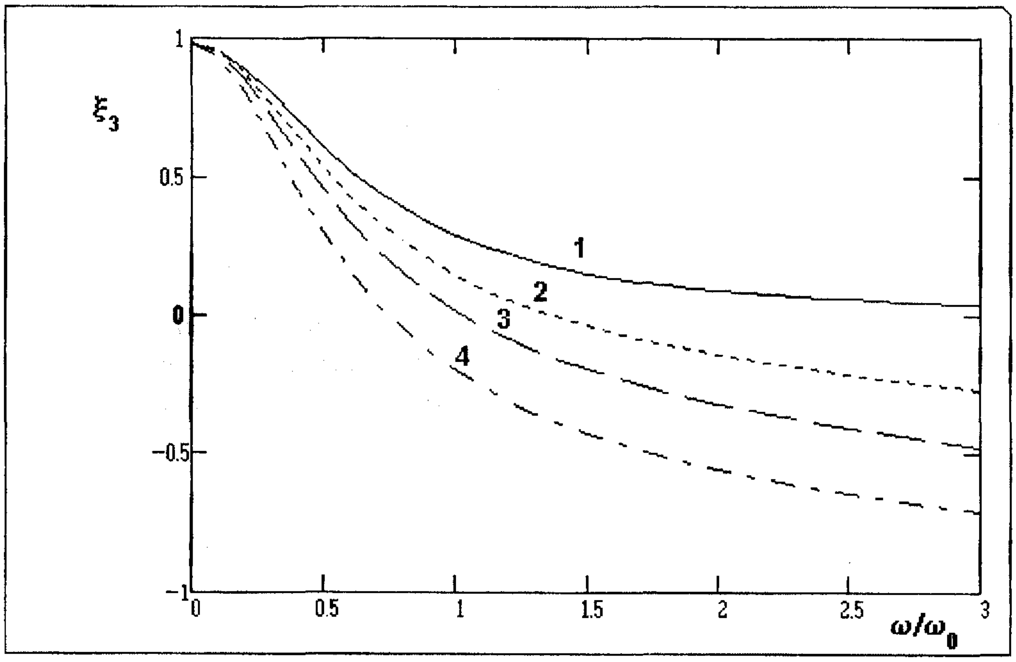

Fig.2. The linear polarization degree ξ_3 as a function of emitted photon energy ω and the relation $\frac{U}{R}$: 1-$\frac{U}{R}$=0; 2-$\frac{U}{R}$=0,1; 3-$\frac{U}{R}$=0,2; 4-$\frac{U}{R}$=0,4, γO_d=0,5.

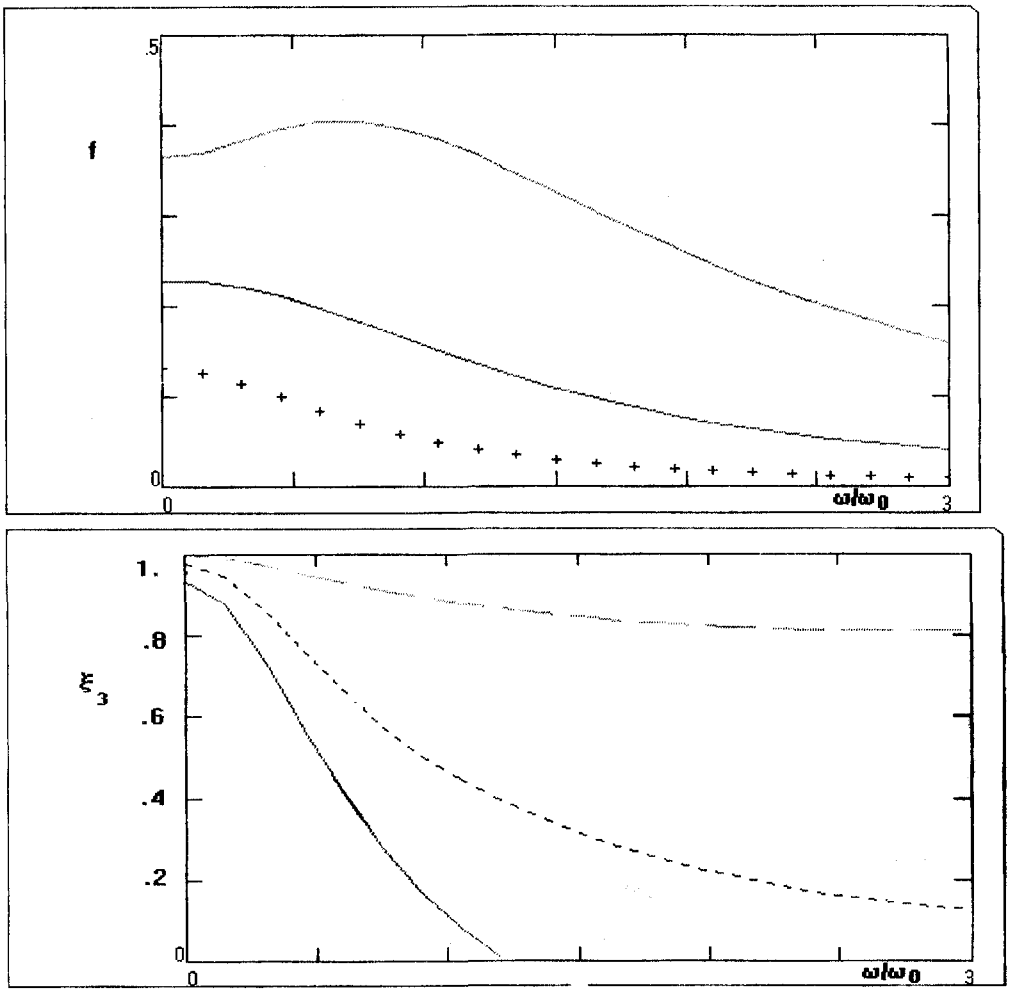

Fig.3. The influence of nonaxial collimation on the radiation spectrum f and the linear polarization degree ξ_3: 1-$y=\gamma(\psi_x-O_x)=0$; 2-$y=0,5$; 3-$y=0,8$, $\gamma O_d=0,5$, $\frac{U}{R}=0$.

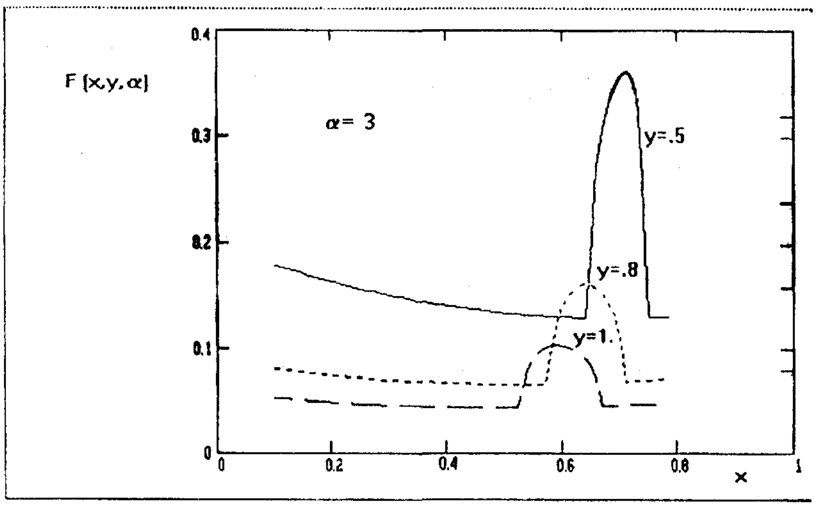

Fig.4. The emission spectrum F as a function of the observation angle ψ_x-θ_x: $x=\frac{\omega}{\varepsilon}$, $y=\gamma|\psi_x-\theta_x|$, $\alpha=\frac{2g\gamma}{m}$.