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STRUCTURAL RESONANCES IN X-RAY SPECTRA OF RADIATION BY FAST CHARGES IN ELECTRON MATTER

V. K. Grishin

Skobeltsyn Institute of Atomic Physics of Lomonosov Moscow State University

The practical possibility of observation of coherent polarizing bresstrahlung radiation (PB) by fast charges, arising at dispersion of own electromagnetic field of fast charges on atomic electrons in the condensed media, is considered. PB effect of inhomogeneity of medium electron distribution, appearing due to intratomic bonds and resulting in produce of radiation intensity oscillation, is noted. Main PB peak placed in low-frequency region has most intensity that corresponds to maximal coherency in radiation process. Besides in PB spectrum there are additional peaks in which differences of photon phases are multiple π. Influence of structure ordering of media on characteristics of coherent peak PB is analyzed. It is shown that medium structure regularity even low order results in sharp low-frequency displacement of coherent peak, though its amplitude grows proportionally to a square of ordering length («effect of diffraction grating»). Therefore possibility of its observation becomes rather problematic as here in low-frequency region there is also effect of coherent radiation suppression caused by self-suppressing of amplitudes of incident fast charge field. On the contrary, amplitudes of additional peaks, being proportional to square of ordering length, do not change position. In result, in the regular media first additional coherent peak grows sharply, that appropriates to condition of occurrence of PB kind — Resonant transition radiation.

INTRODUCTION

At present properties of fast charges radiation stimulated by theirs interaction with the atomic electrons in a condensed matter are lively discussed. This kind of X-ray radiation is very sensible to the character of electron distributions in matter [1]. Therefore its study permits to obtain a very useful information about the matter structures.

At first it is very important to research the inhomogeneity effect of electron density distribution in medium and its structural ordering. It is known that electronic distributions in a media, despite of the broad variety, have one prominent feature. Interatomic bonds in media are realized by electrons of external atomic shells, while internal electronic shells are practically not perturbed. The external electronic shells are extended in directions of the next atoms. Because of that the electronic distributions of media represent alternations of more dense and practically empty zones of space which have regular or chaotic character depending on a degree of medium structure ordering.

This specific character of the electron distribution is reflected on the properties of fast particles radiation in condensed media. In particular here some very interest effects may be predicted. Consider an elementary structural cell of medium, i.e. an elementary volume of the medium space with a «hollow» at center surrounded by bond electrons. Due to the bond electrons are concentrated near to cell walls, the sharply expressed interference effects in radiation of fast charges (the polarization bremsstrahlung radiation (PB) of moderate relativistic electrons is considered) are occured. If the difference of phases of signal radiation on various cell sides amounts to be multiple of π, the radiation intensity is weakened or amplified, and signal oscillations are observed.

Moreover it is possible to expect that the greatest radiation intensity must be watched in low frequency range of a spectrum (in a range of energy of photons less than 1—2 keV). Here the wavelength of radiation becomes so major that the process of radiation

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covers the majority of the medium electrons, and the radiation acquires the coherent character.

Then it is very important to analyze the influence of structure medium ordering on oscillations and coherent effects. The structure regularity even of the short-range order must sharply displace, because of «effect of a diffraction grating», the coherent peak to the low frequency range (note that this low frequency shift has been marked experimentally and theoretically [2—4]), and its amplitude increases proportionally to quadrate of ordering length.

Therefore even at short ordering of the matter, the possibility of observation coherent radiation becomes rather problematic since the suppression of coherent radiation stimulated by self-annihilation of a fast incident charge field has an effect also in low frequency range. In the whole peaks increase sharply in X-ray radiation spectra accordingly to periodicity length of matter that corresponds to a condition of resonant transition radiation.

Peculiarities of the manifested effects in carbon structural micro cells are described below.

ANALYTICAL DESCRIPTION OF PB IN MEDIUM

Polarizing radiation, including its kinds, can be described as dispersion of own electromagnetic field fast charge on medium electron. We shall be limited to a case of poorly relativistic particles when the relativistic factor γ of electron and region of radiation frequencies ω satisfy to a ratio $\omega^2 >> \gamma^2\omega_0^2$. Electric field of the fast charged particle moving parallel an axis $\mathbf{z}$ with velocity v past a medium electron with the impact parameter b, can be presented as a wave package, termed frequently a package of virtual (or equivalent) photons [5, 6]. Cross electric fields (cross field is axial-symmetric in relation to the trajectories of a fast charge; longitudinal fields is much less even for poorly relativistic charge)

$$E(t,z,b) = \int_{-\infty}^{\infty} E(b)_\omega \exp(-i\omega(t - z/v))\, d\omega \quad (1)$$

has Fourier's component

$$E_\omega = e\zeta K_1(\zeta)/(\pi b v) = e\zeta K_1(\zeta)/(\pi v)E_{0\omega},$$
$$\zeta = (\omega b)/(\gamma v),$$

where K_1 is modified Hankel's function, e is fast particle charge. Quantity of E_ω remains approximately to a constant up to $\zeta \simeq 1$, and then sharply decreases. Wave vectors in a package is $\mathbf{k}_\omega = \mathbf{n}\omega/v$ unit vector $\mathbf{n}$ is directed along the axis $\mathbf{z}$ *.

As in real experiment energy of photons in PB exceeds bond energies of electron in media, process of PB is in essence a kind of collective Compton's dispersion. Let's select some volume of media containing Z electrons. These electron, being on distances b_s where $s = 1..,Z$ from a trajectory of the incident charge, are making cross oscillations forced by field E_ω, radiating (i.e. re-scattering) photons of the same frequency.

Following known procedures [7, 8], it is possible to receive the spectral- angular density of energy radiated by the charged particle along a vector $\mathbf{n}'$ at an angle ψ with respect to the axis z (further at calculations the orthogonal system of coordinates (x, y, z) is used, and the plane (x, y) coincides with $((\mathbf{n},\mathbf{n}') -)$one):

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^4}{8\pi m^2 c^3}\left\langle \left| \sum_{s=1}^{Z_f} [\mathbf{n}'\mathbf{E}_{\omega,s}] \exp(-i\mathbf{q}_\omega \mathbf{r}'_s) \right|^2 \right\rangle, \quad (2)$$

where $d\Omega$ is an element of the solid angle, a vector $\mathbf{q}_\omega = \mathbf{k}'_\omega - \mathbf{k}_\omega$, $q_\omega \simeq 2(\omega/c)\sin(\psi/2)$ as $v \sim c$, $\mathbf{k}'$ is the wave vector of photons along $\mathbf{n}'$, and $\mathbf{r}_s$ are radius-vectors of medium electrons.

Vector product $[\mathbf{n}'\mathbf{E}_{\omega,s}]$ is calculated ratio (1) (therefore the medium electrons have various values of impact parameters b_s; in the chosen coordinate system $b_s^2 = x_s^2 + y_s^2$).

At last, brackets $\langle\ \rangle$ mean that it is necessary to average the whole ratio (2) over the cross distribution of trajectories of incident particles and the distribution of medium electrons in the cell.

By this way the ratio (2) is transformed to a ratio

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^6}{8\pi^3 m^2 c^5}(Z(Z-1)Q_{coh} + ZQ_{inc}), \quad (3)$$

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[*] Here it is not taken into account screening influence of medium by virtue of the mentioned above condition $\omega^2 >> \gamma^2\omega_p^2$. Notice that after decomposition on cross spatial Fourier's component, representation (1) is resulted to the traditional wave description of a fast charge field [3, 7].

where

$$Q_{coh} = \left(\left\langle[\mathbf{n}'\mathbf{E}_{0\omega,\mathrm{s}}]\cos(\mathbf{q}_\omega \mathbf{r})\right\rangle\right)^2 +$$
$$+\left(\left\langle([\mathbf{n}'\mathbf{E}_{0\omega,\mathrm{s}}]\sin(\mathbf{q}_\omega \mathbf{r})\right\rangle\right)^2,$$
$$Q_{inc} = \left\langle[\mathbf{n}'\mathbf{E}_{0\omega,\mathrm{s}}]^2\right\rangle.$$

Scalar product $\mathbf{q}_\omega \mathbf{r} = q_1 x + q_2 z$ at $q_1 = -q_\omega \cos\psi/2$, $q_2 = q_\omega \sin\psi/2$.

Formfactors Q_{coh} and Q_{inc} characterize coherent and not coherent contributions of cell electrons in total radiation. Obviously, with other things being equal, contributions the coherent and not coherent components time differ approximately in Z. Therefore following traditional practice, further we shall be limited to the detailed analysis of coherent effects.

Let's address to concrete modelling. A relative part of electrons participating in interatomic interactions is greater in media of light elements (further light elements will be taken in account at estimations). For example, in carbon condense media the electrons of external S-and P-shells provide interatomic bonds. But electrons K-shell are practically not perturbed.

Real medias differ by a broad variety of structures. For revealing some general features of PB in condensed media, the following simple model is used. We shall put that the elementary cell coincides with the elementary volume of a cubic lattice. The lattice constant $a \simeq 0.2$ nm (that corresponds to average density, for example, in carbon media). Here eight atoms, located in apexes of the cell, exchange by external electrons, forming electronic clouds extended at the directions of apexes. The central region of the cell remains more or less free.

Therefore it is possible to describe the distribution of electronic density external electrons as follows:

$$\rho(\mathbf{r}) = [1 - \exp(-g^2(x^2 + y^2 + z^2))]/m, \qquad (4)$$

where the norm M gets out so that

$$\int\limits_V \rho(\mathbf{r})\, d\mathbf{r} = 1$$

where V is the volume of a cell, and parameter g characterizes the distribution homogeneity of an interatomic electronic cloud.

Internal electron (quantity Z_{int}) fill essentially smaller volumes near to apexes of the cell (really, average radius of K-orbits for carbon is about 0.01 nm [8]). It is possible to simulate them as δ-distributions.

Thus, in aggregate the average full electron number Z in a cell coincides with the full electron number in a separate atom.

In a result, as a first approximation

$$Q_{coh} = ((Z - Z_{int})\int\limits_V \frac{x\sin(q_1 x)\cos(q_2 z)}{x^2 + y^2}\rho(\mathbf{r})\, d\mathbf{r} + \qquad (5)$$
$$+Z_{int}\sin(q1a)\cos(q2a)/2a)^2\cos^2\psi/Z^2,$$

where it is supposed, that in low-frequency region the condition $\zeta < 1$ is carried out.

The effects, connected to presence in the medium a structure (periodicity) with near or large length of ordering, may be described by means of including in volume of radiation not one but N cells built along the axis $\mathbf{z}$. Thus the number N will represent real ordering, i.e. the length of coherent periodicity at radiation. Then the effective formfactor

$$Q(N) = Q_{coh}F_N^2;$$

$$F_N = \cos((N-1)q_2 a)\frac{\sin(Nq_2 a)}{sin(q_2 a)}. \qquad (6)$$

Obviously the maximal effect is observed at frequencies if the phase shift 2 $q_2 a$ between the next cells appears multiple 2π when intensity of radiation grows N^2 times. Thus for crystal media the maximal number N_{max} is limited by the self-absorption length of radiation, by the dispersion length of incident electron and so on, and it can reach several tens.

On the contrary, for amorphous structure number N_{max} really makes only some units. At total, the formfactor $Q(N)$ analysis allows to reveal influence of media structures on spectral-angular PB properties.

DISCUSSION OF RESULTS

In result formfactors Q_{coh} and $Q(N)$ have a number of rather characteristic features. Some results of numerical calculations are submitted in Fig. 1—3 at $Z = 6$, $Z_{int} = 2$. Fig. 1 presents the dependence of formfactor Q_{coh} for a single cell (i.e. at $N = 1$; parameter $F_N = 1$)) on photon energy for various angles $\psi = \pi/4$ and $\psi = 3\pi/4$ of radiation.

The common moment for both diagrams is occurrence of coherent peak of Q_{coh} in low-frequency region and its oscillation at more high-frequency region. Occurrence of Q_{coh} oscillations finds a simple physical explanation: minima and maxima in oscillations correspond situation when the difference of radiation phases (under given angle) on various sides of a cell amounts to multiple π.

By this the dependence of Q_{coh} on a angle of radiation ψ is manifested in a displacement of spectrum along the photon energy scale since $\hbar\omega = q_{\omega}\hbar c/(2\sin(\psi/2))$ and as consequence in change of the oscillation amplitudes. As to direct angular dependence of coherent formfactor (see factor $\cos^2\psi$ in ratio (5)), it is more complex in real conditions because it is necessary to take into account a possible asymmetry of a medium density on the axis y.

Besides note that the observed sum PB includes the incoherent component with a traditional angular dependence which is proportional to factor $1+\cos^2\psi$. In any case PB intensity has a minimum in $\psi \sim \pi/2$ region.

Fig. 2 illustrates influence of inhomogeneity (i.e. at the big or smaller values of parameter g) in the distributions of the electron density in a cell.

Fig. 3, 4 represent the dependence formfactor $Q(N)$ on photon energy at various N_{max}.

It is marked a notable low-frequency displacement of the coherent region already at $N_{max} > 2,3$. Coherent PB spectrum is here a result of two competing processes. First, radiation interferences of the next cells, resulting in narrowing of sum radiation peak at simultaneously its amplitude amplification (proportionally N^2). Second, self-suppressing of radiation at $\omega \to 0$ owing to mutual anti-polarity of the incident particle field components (see above).

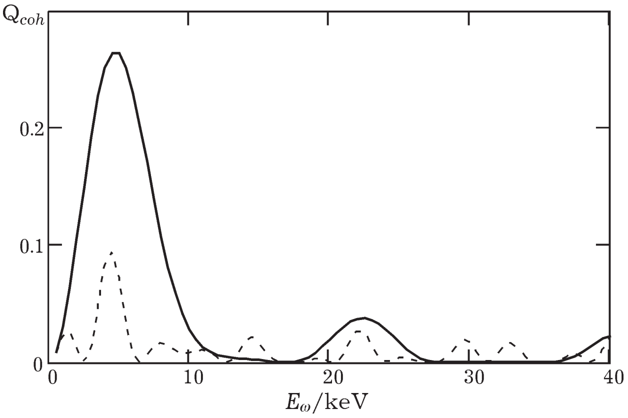

Fig. 1. Formfactor Q_{coh} at various photon energy E_{ω} in cubic cell of medium with $Z=6$; $Z_{int}=2$ at $a=0.1$ nm at various angles ψ of radiations. Continuous curve — $\psi=\pi/4$, dash curve — $\psi=3\pi/4$

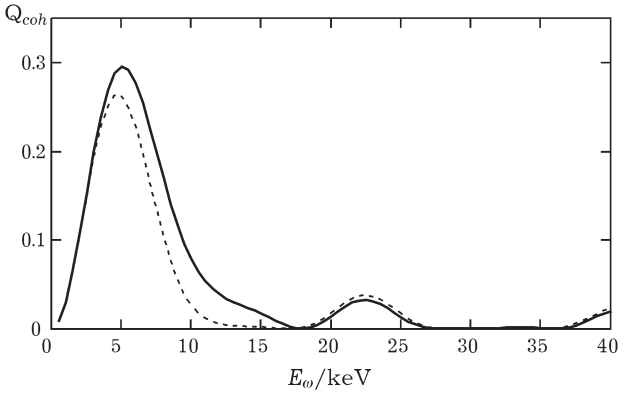

Fig. 2. Formfactor Q_{coh} at various photon energy E_{ω} in cubic cell of medium with $Z=6$; $Z_{int}=2$ at $a=0.1$ nm at angle $\psi=\pi/4$ of radiation at various values of parameter g. Continuous curve — $g=5$, a dotted curve — $g=1$

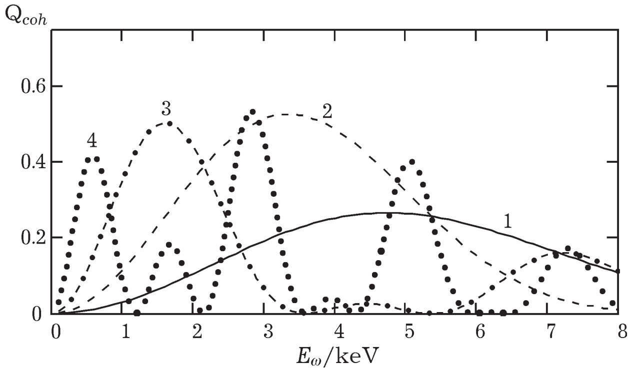

Fig. 3. Formfactor $Q(N)=Q_{coh}F_N^2$ at various values N_{max} and photon energy E_{ω} in region of first coherent peak for $\psi=\pi/4$. Curve 1 — $N=1$, curve 2 — $N=2$, curve 3 — $N=4$, curve 4 — $N=10$

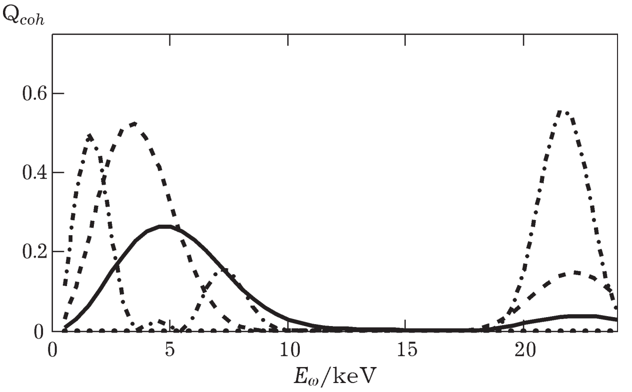

Fig. 4. Formfactor $Q(N)=Q_{coh}F_N^2$ at various values N_{max} and photon energy E_{ω} in region of first and second coherent peaks for $\psi=\pi/4$. Continuous curve — $N=1$, dash curve — $N=2$, a dot-dash curve — $N=4$

Therefore even for media with the small length of ordering, the experimental observation of coherent PB becomes problematic. In connection with said, there are explained conclusions of work [2] (where properties PB in dense amorphous carbon, i.e. in media with extreme small ordering, were investigated), that the coherent effect is necessary to expect in similar medium only for photons with energy at 1—3 keV range. Note once more, that PB sum intensity is defined partly by incoherent component which has an additional logarithmic rise in low-frequency region. As follows from procedure of averaging of the factor Q_{inc} on cross distribution of incident particles, the last effect is defined basically by the internal orbits electron contribution. So the marked rise can have an notable effect only in heavy elements.

Emphasize that amplitude of coherent peaks for a single cell is much below than PB burst in low-frequency region. Nevertheless, already for the several built cells the oscillation amplitude sharply grows (and the first peak will be correspond to one of PB kinds — resonant transition radiation), see Fig. 4.

It is very interest that PB properties indicated above may be also observed in radiation of such «macro—micro» objects as fullerenes [9, 10].

At an estimation of an experimental output here first of all we have to take into account that among collateral facts the most intensive is an usual bresstrahlung radiation. But the latter is concentrated in the angular interval $\Delta\psi \simeq 1/\gamma$. Therefore PB becomes dominant for the big angles of observation.

Thus, despite of modelling character of used descriptions, consideration has shown that PB observation allows to receive the additional information on media tructure.

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