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SCREENING EFFECT AND NANO-DIAGNOSTICS IN STRUCTURED SUBSTANCE BY ELECTRON BREMSSTRAHLUNG RADIATION

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Abstract

Possibility of atomic nucleus structure diagnostics in mutter using bremsstrahlung radiation (BR) by relativistic electrons in real condition of nucleus electric field screening by medium electrons is discussed. An alternative method of BR spectrum calculation is stated that allows to establish original connection of frequency - angular BR properties and the relativistic factor of radiating electron for light and heavy elements. It is shown that despite of sharp falling of BR intensity in comparison with radiation on a "naked" nucleus medium electrons suppress not completely BR that keeps an opportunity of its use for media structural diagnostics.

В.К.Гришин

ЭФФЕКТ ЭКРАНИРОВКИ И НАНО-ДИАГНОСТИКА СТРУКТУРИРОВАННЫХ ВЕЩЕСТВ ТОРМОЗНЫМ ИЗЛУЧЕНИЕМ ЭЛЕКТРОНОВ

Препринт НИИЯФ МГУ - 2007-10/831

Аннотация

Обсуждается возможность диагностики распределения атомных ядер в веществе с помощью тормозного излучения (ТИ) релятивистских электронов в этом веществе с учетом экранирования полей ядер электронами среды. Излагается альтернативный метод расчета спектра ТИ, позволяющих установить своеобразную связь частотно-угловых свойств ТИ для легких и тяжелых элементов. Показывается, что несмотря на резкое падение интенсивности ТИ по сравнению с излучением на "голом" ядре, экранировка не полностью подавляет ТИ, что допускает его использование для структурной диагностики вещества.

1. Introduction

Opportunity of atomic nucleus distribution diagnostics in substance by bremsstrahlung radiation (BR) of accelerated electrons is always been meant to some extent at diverse discussions of the fast charge interaction with condensed media (see, for example, materials of special editions [1,2] etc.).

Here, one of base questions is the correct account of nucleus electric field screening by medium electrons. Screening can render an essential influence on spectral BR character. So, in low-frequency range with length of a radiation wave comparable with interatomic distance in substance (i.e. in a wave diapason which is necessary for structural diagnostics), it is possible to expect en essential BR suppression.

At the same time, nucleus distribution in condensed substances has practically a dot character while electrons (especially that part which is responsible for interatomic interaction) are allocated in all interatomic space. Due to this circumstance, there is an appreciable nonuniformity in spatial distribution of sum electric field of charges in substance. In the result, field screening is enough weak near to atomic nuclei to suppress BR generation. Therefore the estimation of a real situation is rather important for practical diagnostic of substance.

Such estimations are been carried out below for substances of light and heavy elements. The special attention is given to the analysis of coherent BR conditions. Concrete considerations are based on the assumption that the intensity of coherent BR by incident relativistic electrons is the result of their interaction with the electric field of all charge particles in medium.

2. Analytical description of BR on single nucleus

First, let's consider BR by relativistic electron in the field of a single nucleus with a charge $+Ze$ immersed in a screening cloud of Z electrons. The geometry of particles interaction is presented in Fig. 1. Here the Cartesian coordinates (X, Y, Z) are used with the Z axis parallel to the incident electron velocity $\vec{v}_e$. Vector $\vec{\rho}$ with coordinates $(x, y, 0)$ is the impact parameter of incident electron with respect to the nucleus placed in the beginning of coordinates. The nucleus are surrounded by medium electrons (the latter ones are not indicated in Fig.1).

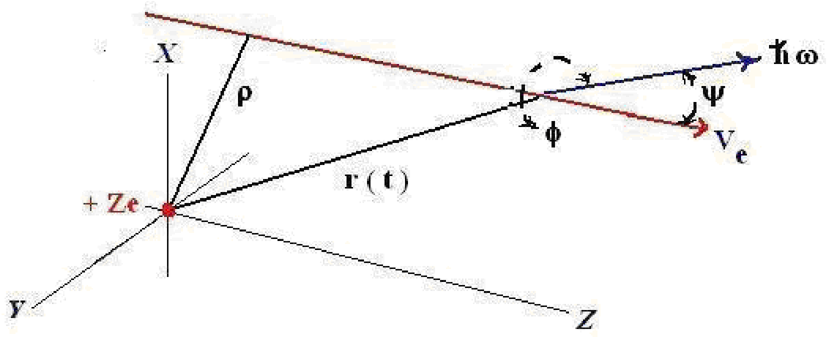

Figure 1: Scheme of en electron radiative interation with Ze-charged nucleus. $\vec{r}(t)$ is the electron vector-radius, $\vec{\rho}$ is the electron impact parameter.

Fast electron, passing some point $\vec{r}(t)$ with coordinates $(x, y, z(t))$, irradiates a photon with an energy $\hbar\omega$ under the angle ψ in parallel the plane (Y, Z) (the plane of radiation is fixed by an angle ϕ at the given direction of the vector $\vec{\rho}$).

Cross component of total electric field of nucleus and screening media electrons can be represent as

$$\vec{E}_{\perp} = \frac{\vec{\rho}\, Q(\vec{r})}{r^3} \tag{1}$$

where $\rho^2 = x^2 + y^2$, $Q(\vec{r})$ is the effective charge creating a field in a point $\vec{r}$.

Assuming that the average distribution of the electron density in substances is symmetric and near to a nucleus it is close to a atomic one which can be described as $n_0\, exp(-\alpha\, r)$ c in the maximal density n_0, we receive

$$Q(r) = Ze\,(1 - \int\limits_0^r n_0\, exp(-\alpha\, r')\, dr') \tag{2}$$

Here α is the screening parameter. The latter can be defined, for example, within the limits of $Fermi - Fok{}^{,}s$ theory according to which half of full electronic charge is locked inside spheres with radius $R_{1/2} \simeq 0.07/Z^{1/3}\, nm$ [3]. Hence, $\alpha \simeq 80\, nm^{-1}$ for light elements and $\alpha \simeq 150\, nm^{-1}$ for heavy ones.

In the result

$$Q(r) \;=\; Ze\,(1 \,+\, \alpha\, r \,+\, \alpha^2\, r^2/2)\, exp(-\alpha\, r) \tag{3}$$

Let's notice that relations (1) and (3) describe correctly limiting cases at $\alpha\, r \,\sim\, 0$ and $\alpha\, r \,\gg\, 1$.

The specified relation allow at once to define screening influence on intensity BR. Radiations. Really, following [4, full energy of radiation makes (it is assumed that a share of photons with the big energy is not great "on the average" also does not change the velocity v_e)

$$\Delta\, J_{rad} \;=\; \frac{2\, e^4}{3\, m^2 c^3} \int_{-\infty}^{\infty} \gamma^2\, \vec{E}_{\perp}^2(t)\, d\, t \tag{4}$$

Here it is taken into account that from a position fast electron, the nucleus field is a variable signal because $r(t) \;=\; \sqrt{\rho^2 \,+\, v^2\, t^2}$.

More detailed representation about character of radiation can be received using $Fourie's$ representation for amplitude of the field cross component:

$$E_{\perp} \;=\; \frac{1}{2\,\pi} \int\limits_{-\infty}^{\infty} E_{\omega}\, exp(-i\,\omega\, t)\, d\omega \tag{5}$$

From here

$$E_{\omega} \;=\; \frac{Ze}{\pi\, v} \left(\eta\, K_1(\rho\,\eta) \,+\, \frac{\alpha^2\,\rho}{2} K_0(\rho\,\eta)\right) \tag{6}$$

where $K_{0,1}$ are $Macdonald's$ functions of the appropriate order and

$$\eta \;=\; \sqrt{\alpha^2 \,+\, \frac{\omega^2}{\beta^2\, c^2}} \tag{7}$$

with $\beta \,=\, v/c.$

Relation (6) allows to calculate spectral-angular characteristics of BR by relativistic electron. Thus it is necessary to take into account all azimuthal directions of a vector $\vec{\rho}$ that is equivalent to averaging on ϕ.

In the result, BR energy relativistic electron in the plane (Y, Z) in an element of the solid angle $d\,\Omega$ and for a frequency interval $d\,\omega$ is equal

$$dj_{\omega} \;=\; \frac{e^4}{m^2 c^3\, \gamma^2}\, \frac{(1 \,-\, \beta\, cos\,\psi)^2 - sin\,\psi^2/2\,\gamma^2}{(1 \,-\, \beta\, cos\psi)^4}\, |E_{\omega'}|^2\, d\,\Omega\, d\,\omega \tag{8}$$

where a frequency ω in the argument η in relation (6) is replaced by a variable

$$\omega' = \omega\,(1 - \beta\,cos\psi) \tag{9}$$

Note this procedure is traditional for spectral theory of radiation by a relativistic charge [4].

Hence the radiation spectrum is defined by the combined argument η which is defined by both the screening parameter α and universal variable ω',, having the same value at various combinations of frequencies and angles of radiation and relativistic factors of fast electron.

It is obvious that influence ω' on character of a radiation spectrum has an effect only at

$$\omega'/\beta\,c \geq \alpha \tag{10}$$

Under an opposite condition,one general spectral feature BR is shown which is characteristic for radiation in absence of screening [5, 6] but is peculiar also to an examined case.

Frequency properties of BR spectrum is defined in (9) by quantity $|E_\omega{}'|^2$ which depends poorly on frequency in the limits specified by relation (10). Therefore a spectrum of the photon density is equal $dj_\omega/\hbar\,\omega$, and it appears inverse proportional to radiation frequency in our case too.

3. Chain of N nuclei

At BR-interaction of fast electrons with set of nucleus, the most interesting situation can be observed in the structured media for example in crystals where there are conditions for coherent BR generation.

For a chain of N nuclei, built along the axis Z with the period $\Delta\,Z = d$ and surrounded by a cloud of screening electrons, energy of radiation

$$dJ_\omega = dj_\omega \cdot G_N \tag{10}$$

where

$$G_N = \frac{sin^2(\omega'\,d\,N/2\,\beta\,c)}{sin^2(\omega'\,d\,/2\,\beta\,c)} \tag{11}$$

4. Basic results

Let's address to primary aim of the present consideration. By ratio (8), screening effect is described by the factor $|E_{\omega'}|^2$. Features of this effect for single atom are illustrated in Fig. 2 and Fig.3 where quantities

$$FC = \frac{2}{\rho_{max}^2} \int\limits_{\rho_{min}}^{\rho_{max}} |E_{\omega'}|^2 \, \rho \, d\, \rho \qquad (12),$$

are submitted. These quantities are describing BR intensities averaged on various impact parameters of radiated electrons at various values of universal energy $\hbar\omega'$ for light and heavy atoms. Here the values ρ_{min} and ρ_{max} have the order of *Compton's* lengths and half of internuclear distance in substance, accordingly.It is necessary to note essential BR suppression, specially at small photon energies and for atoms of heavy elements. Nevertheless in area of photon energies about one keV, interesting for structural researches, BR suppression is not absolute as it is expected. It is connected to that obvious fact that electron screening appears appreciably lowered close to a nucleus.

The said proves to be true, in particular, by a convergence of BR intensities at higher photon energies for various values of α.

Hence, the expectations connected with BR using for of substance structure diagnostics are quite justified, first of all for definition of length of structure ordering.

Note that it is necessary to underline here that, in opposition to traditional x-ray analysis, we say about "direct" radiating research when the target is a radiator and studying object at the same time [7]. Despite of essential suppression of BR signal , coherent amplification in ordering substance allows sharply to increase the signal amplitude and level of diagnostics reliability.

As an example, in Fig. 4 the characteristic peak structure of BR signal, arising at flight of relativistic electron (with $\gamma >> 1$) along a crystal chain of N atoms located with linear periodicity d, is submitted.

Here on vertical axis the reduced quantity $FP = FC \cdot G_N/N^2$ (for light elements; for heavy ones the height of peaks is suppressed approximately in one and a half time). Following relations (10) and (11), peak locations correspond to consecutive changes of a phase of BR signal at 2π.

Thus generalizing this fact, it is possible to conclude that supervision of spectral features of it BR (position of peaks and their sizes) allows to define structural parameters of a crystal lattice and electron distribution .

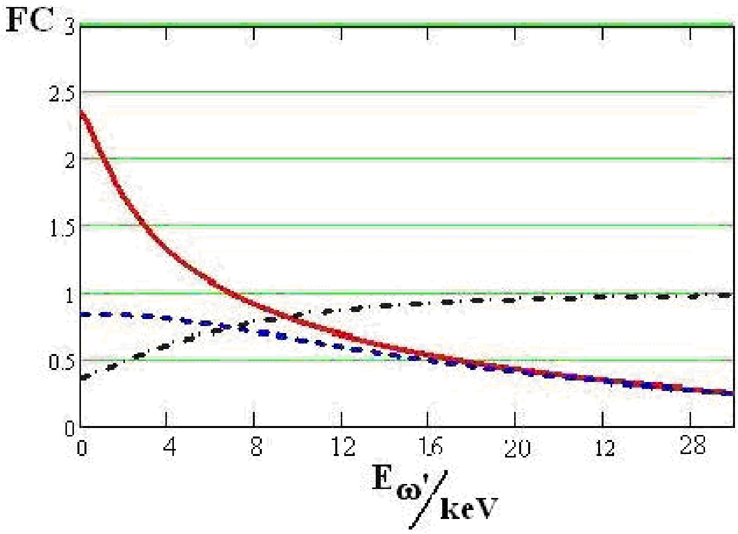

Figure 2: Screening influence on BR intensity of relativistic electron on single atom (light element) at various photon energies with universal frequency ω'; vertical axis - factor FC (in arb. un.) with radius of averaging $\rho_{max} = 0.18nm$; continuous curve -$\alpha = 0$ (" a naked nucleus "); dotted line - $\alpha = 80\,nm^{-}1$; dot-dash line - their relation.

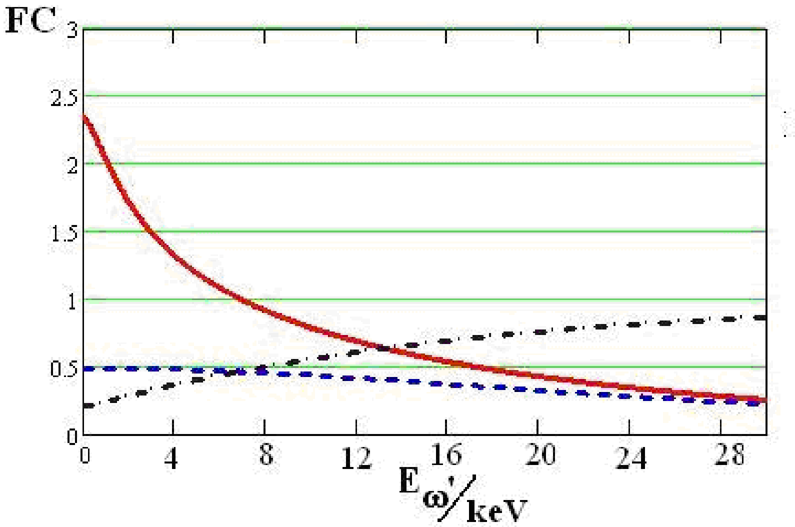

Figure 3: Screening influence on BR intensity of relativistic electron on single atom (heavy element) at various photon energies with universal frequency ω'; vertical axis - factor FC (in arb. un.) with radius of averaging ρ_{max} = $0.18nm$; continuous curve -α = 0 (" a naked nucleus "); dotted line - α = 150 $nm^{-}1$; dot-dash line - their relation.

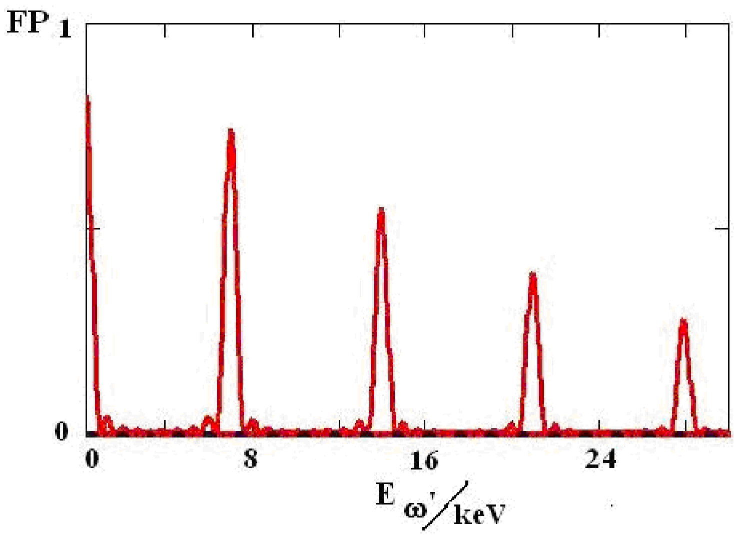

Figure 4: Peaks structure of BR by relativistic electron on atom chain at different photon energies; chain period d = 0.36 nm.

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