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Interaction of high energy gamma-quanta with crystal surface: Classical reflection and interference phenomena

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ABSTRACT

The interaction of high energy gamma-quanta with crystal surfaces under small sliding angles is considered. It is shown that under certain conditions, such interactions can be described in classical wave theory formalism up to the energies, exceeding 10^{11} eV.

1. Introduction

The interaction of high energy photons with matter is usually considered within the frameworks of the quantum electrodynamics perturbation theory as individual acts of either emission or absorption of photons, interacting with such elements of matter as electrons in atoms (discrete spectra of emission and absorption), free electrons (Compton effect) etc. (see, for example, [1–2]). At the same time in classical electrodynamics electromagnetic radiation is considered as a macroscopic wave, which can be reflected or refracted at the interfaces of continuous media with different refractive indexes, changing at this border the propagation velocity (see [1,3]). Classical waves are also subject to such phenomena as interference and diffraction, which, together with classical reflection and refraction phenomena, are not so simple (if generally possible) to describe *quantitatively* within the formalism of quantum electrodynamics.

It is usually accepted that if the photon wavelength λ is comparable or much longer than a typical distance between the elements of matter d (in condensed matter typical distance between atoms $d > 0.1$ nm), it may coherently interact with many charged particles simultaneously. Quantitative description of such interaction goes far beyond the frameworks of the perturbation theory (see, for example, [4–6]). In this area it is much more convenient and effective to describe electromagnetic phenomena in terms of the classical wave theory [1,3].

The shortest wavelength photons, for which the classical wave properties (reflection, diffraction (in a crystal) etc.) are explicitly or just somehow manifested, are X-ray (Bragg and Laue diffraction phenomena [7,8]). Their wavelengths are still comparable with typical distances between atoms in condensed matter. Photons with shorter wavelengths and higher energies ($\lambda < 0.01$ nm $\ll d$; $\varepsilon > 100$ keV), produced in nuclear reactions or of cosmic origin [9] and distinguished by a separate frequency range, are named gamma-rays. It is usually accepted that gamma-quanta are interacting with structure elements of matter as individual quanta and hardly reveal any classical wave properties.

On the contrary. in the cases of charged particles (electrons, protons etc.), sliding along smooth crystal planes, coherent interaction with many atoms simultaneously can be rather easily described as interaction with averaged homogeneous crystal plane potential (well known "channeling phenomena" – see, for example, [4–5]). Channeling phenomenon becomes possible when a charged particle is propagating along crystal plane under small angle θ, which is smaller than the critical Lindhard channeling angle θ_L [9]:

$$\theta < \theta_L \sim (2U/E)^{1/2} \ll 1 \tag{1}$$

where E is the relativistic particle energy; U is the effective height (or depth) of the continuous crystal plane potential (~20–50 eV for planar channeling in most of crystals [4]). If, for example, the particle has an energy $E \sim 10$ GeV, we obtain $\theta_L \sim 10^{-4}$. In the case when charged particle approaches the outside smooth crystal sur-

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face at sliding angle (1), it will reflect from the surface coherently under the reflection angle, equal to the incidence angle.

To certain extent some analogs of channeling phenomena are possible to find even for neutral particles, such as gamma-quanta or neutrinos (see, for example, [10,11]). We may expect that neutral particles, interacting under small sliding angles with smooth surface, may also reflect from it. Unfortunately the description of such coherent interactions in terms of quantum electrodynamics is much more complicated and not so obvious as for charged particles.

In this paper we are going to propose an experimental scheme and the explanation, based on relativistic principles, why the classical wave approach can be applied even for gamma-quanta with energies, exceeding 10^{11} GeV in the case, when they are approaching a smooth crystal surface under small sliding angles. In this case we could experimentally observe many classical wave optics phenomena, such as classical reflection from the surface and even classical interference effect.

2. Observation of gamma-quanta in the frames of relativistic co-moving reference frame (CRF)

According to the general principle of relativity, all physical laws and phenomena observed from different inertial reference frames should work and reveal themselves in one and the same way. In particular – if in some inertial reference system a wave or a particle reflects from a surface classically – it will behave the same way when observed from any other reference system. We are free to select the most convenient inertial reference frame.

In our case we consider the situation when a high energy photon collides with smooth condensed matter surface (crystal surface) under small sliding angle $\theta \ll 1$ in the *relativistic co-moving reference frame* (CRF) (see Fig. 1).

We define the CRF as the system, moving along the surface (along the axis OX) with the velocity $v = c \cos\theta$, where $c = 3 \cdot 10^8$ m/s is the light velocity. The observer in the CRF is all the time located as if “under the photon”. It is obvious, that the observer cannot “observe” the photon, moving in vacuum, until it hits his eye. But finally in CRF the photon will hit it. We introduce the CRF system for one important reason: as we will see further in this reference frame all the transformation formulas for energy and wavelength of a photon will be sufficiently simplified and look much more transparent.

We are going first to answer two questions:

The first question: what will be the photon wavelength λ^*, as observed from the CRF? We shall take into account the relativistic Doppler effect (see [1,3]):

$$\lambda^* = \lambda((1 + v/c)/(1 - v/c))^{1/2} = \lambda((1 + \cos\theta)/(1 - \cos\theta))^{1/2} = \lambda/\mathrm{tg}(\theta/2) \approx 2\lambda/\theta \gg \lambda \tag{2}$$

The photon wavelength λ^* observed from the CRF at small sliding angles $\theta \ll 1$ will be *much bigger* than the wave length of the same photon λ in laboratory system and may be comparable with interatomic distances in crystal. *The course to classical wave phenomena is going to be opened*!

The second question: at which angle θ^* the photon will approach the observer in the CRF (from the point of view of the observer)? It may seem that when the observer is always located “under the photon”, it will hit him vertically. It fact it is not so. Photon can be treated as a quantum wave, moving with the light velocity. It’s wave surfaces in the CRF may be declined. An observer will register the photon as if coming from the point S^* (see Fig. 1), where the photon source S is located, as it is seen from the CRF. If in the laboratory system the source S is located at the distance L (measured along OX axis) from the point of contact of photon with the surface, then in the CRF it will be seemingly located in the point S^* at the closer distance

$$L^* = L(1 - v^2/c^2)^{1/2} = L(1 - \cos^2\theta)^{1/2} = L\sin\theta, \tag{3}$$

due to the length relativistic Lorentz contraction effect (see, for example, [1,3]). Thus the angle θ^* equals (see the drawing at Fig. 1):

$$\mathrm{tg}\ \theta^* = L\ \mathrm{tg}\ \theta/L^* = \mathrm{tg}\ \theta/\sin\theta = 1/\cos\theta \tag{4}$$

If, as in our case, the incidence angle θ in laboratory system is small $(\theta \ll 1)$ then $\mathrm{tg}\ \theta^* \approx 1 \geqslant \theta^* \approx \pi/4$. One should agree that the result is not obviously expected!

3. The criteria of gamma-quanta reflection from the crystal surface

Let us answer one more question: how does the crystal surface look like when observed from the CRF? This look is also influenced by the length relativistic Lorentz contraction effect [1,3]. As the result, the seeming distances between atoms along the direction of the CRF movement (axis OX) will be contracted down to the value

$$d^* = d(1 - v^2/c^2)1/2 = d\ \sin\theta \approx d\theta \ll d \tag{5}$$

At the same time in the transverse direction (into the depth of the crystal) the distances between atomic planes will seem to be the same as in laboratory system (see Fig. 2):

In the CRF the crystal looks like a set of very densely packed parallel atomic planes with interatomic distances $d^* = d\ \ \theta \ll d$, separated by inter-plane distances $d \gg d^*$. If the wave length of photons in RCF $\lambda^* = 2\lambda/\theta$ is much bigger than $d^* = d\ \theta$, they should (may) reflect from the smooth surface coherently according to the classical wave optic laws. If $\lambda^* < d\theta$ photons will more probably pass through atomic planes and interact with single atoms. With

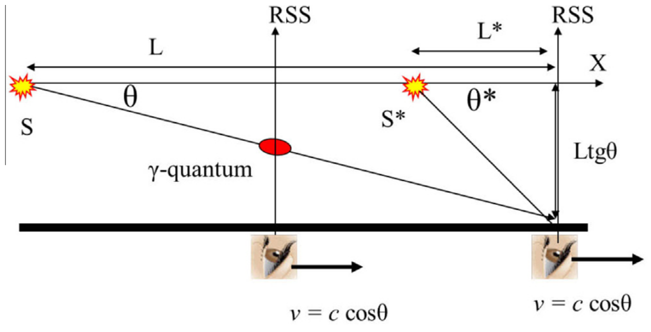

Fig. 1. The experimental scheme and the relativistic co-moving reference frame (CRF).

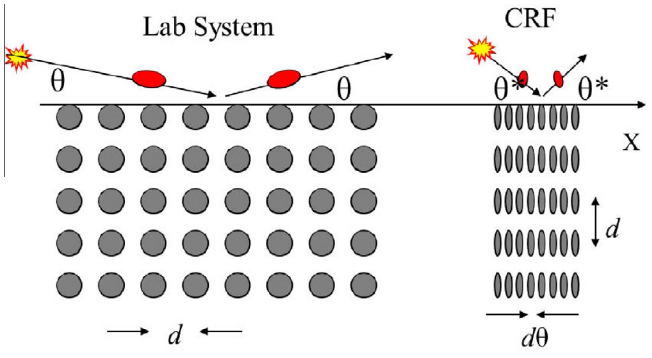

Fig. 2. Crystal planes as seen from the laboratory system and from the CRF.