THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF THE LANDAU-POMERANCHUK-MIGDAL EFFECT IN AMORPHOUS AND CRYSTALLINE MATTER

N.F. Shul'ga, S.P. Fomin

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
e-mail: sfomin@kipt.kharkov.ua

The brief review of theoretical investigations carried out in NSC KIPT on the problem of multiple scattering effect on radiation of high energy particles in matter is presented. The comparison of results of the theory with experimental data obtained recently on accelerators of SLAC and CERN at the study of the Landau-Pomeranchuk-Migdal effect in amorphous and crystalline matter is carried out.

PACS: 11.80.Fv; 13.40.-f; 41.60.-m

1. INTRODUCTION

The successful splitting of the lithium nucleus in UFTI (now NSC KIPT) in 1932 became a stimulus for further broad theoretical and experimental investigations in the field of nuclear physics and physics of accelerators. Researches in these directions are carried on practically during all the time of UFTI existence. Creation of the electron accelerator with the energy up to 2000 MeV in UFTI in 1965 opened new possibilities for investigations in the field of nuclear physics, connected with the research of electro- and photonuclear reactions in this range of the energies. For realization of the researches of photonuclear reactions the beams of monochromatic and polarized gamma-quanta are required. One of perspective methods of such beams production was designed in UFTI in 1960s. This method is based on the process of coherent radiation of ultra relativistic electrons in aligned crystals. Now this method is utilized at many accelerating centers of the world for production of monochromatic and polarized gamma-quanta beams.

The theoretical and experimental investigations of interaction processes of relativistic electrons with crystals carried out in UFTI at the beginning of the 1970s have led to not only interesting but sometimes even paradoxical results. Thus, in particular, it appeared, that at a small angle of particle incidences on a crystal relative to one of its crystallographic axes the radiation by electrons and positrons essentially differs, in spite of the fact that the radiating particles are ultra relativistic. The existing by then theory of coherent radiation of ultra relativistic electrons in a crystal was grounded on the first Born approximation of a quantum electrodynamics. Within the framework of this theory the cross-section of bremsstrahlung does not depend on a sign of a particle charge, so, electrons and positrons should radiate equally. It was revealed also, that the angular distributions of particles scattered by aligned crystal essentially differ from angular distributions of particles in an amorphous medium.

What was also paradoxically is the following. The analysis of applicability conditions of the Born approximation for describing of particle radiation in a crystal, carried out in 1970s, showed, that this approximation fails fast with the decrease of particle incidence angle relative to a crystal axis. Thus, it turned out that practically all experiments on check of predictions of the Born theory of coherent radiation were carried out under the conditions, when the applicability conditions of the Born approximation for describing of particle interaction with crystal are not fulfilled. And in some cases the good consent between the experiment and the theory was reached in the domain, where the theory does not work. All this required a detail research of interaction processes of high energy particles with crystals under the conditions, when the Born perturbation theory is inapplicable. The state of theoretical and experimental researches and the main results obtained in KIPT in this field between late 1960s and 1998 is observed in Refs. [1,2].

The detailed research of processes of high energy particle interaction with aligned crystals out of the domain of applicability of the Born perturbation theory also stimulate a number of other directions of study of particle interaction with intensive external fields and unregulated (amorphous) media. One of such directions of investigations falls into the Landau-Pomeranchuk-Migdal effect (LPM effect) that is the multiple scattering effect on radiation of ultra high energy electrons in amorphous medium [3-5]. In spite of the fact that this effect was predicted at the beginning of 1950s the new interest to the LPM effect has arisen at the end of 1970s. It was caused by the following. In Refs. [6-9] it was shown, that in crystals the multiple scattering of particles in some cases could essentially exceed the scattering in an amorphous target of the same thickness. It means, that in a crystal there should be an analog of the LPM effect, moreover it should appear at lower energies of electrons and in a broader spectral range of radiation.

Besides that, the searches of methods, permitting to describe interaction of high energy particles with crystals outside of the domain of applicability of the Born perturbation theory, led to the methods, which opened possibilities for a new view on the problem of the LPM effect and searching common regularities between processes of particles interaction with crystal and amorphous medium.

The new interest to the LPM effect, which has been observed lately, is connected to the development of a new generation of accelerators of super high energies. The reason is the following. The multiple scattering effect on radiation increases squared with electron energy increasing. It leads to a considerable distortion of the standard Bethe-Heitler's spectrum of bremsstrahlung and electron-positron pair production, and, hence, the development of electromagnetic cascades in substance at high energies will be influenced essentially. Therefore it is necessary to take into account the LPM effect when designing detectors and radiation protection for ultra high energy accelerators and also in cosmic rays physics. Because of this, the special experimental investigation of the LPM effect was carried out recently in SLAC (experiment E-146) Refs. [10-13]. This experiment confirms the main predictions of the Migdal's theory of the LPM effect for relatively thick targets; it also shows a number of problems for describing radiation in a thin target case. This initiated a number of new theoretical works on this problem [14-22].

In the present paper we shall consider briefly some results obtained in NSC KIPT when studying the LPM effect and close effects.

2. THE LANDAU-POMERANCHUK-MIGDAL EFFECT

The process of radiation of a relativistic electron develops in a large spatial region along the direction of particle motion, which is called the coherence length of radiation process. This length grows fast with particle energy ε increasing and with decreasing of emitted photon energy ω [4,5]:

$$l_c = \frac{2\varepsilon\,\varepsilon'}{m^2\omega}, \qquad (2.1)$$

where m is the electron mass and $\varepsilon' = \varepsilon - \omega$. If in limits of this region an electron interacts with one atom of a medium, the cross-section of bremsstrahlung is determined by the Bethe-Heitler formula [4,5,23]

$$\frac{d\sigma_{BH}}{d\omega} = \frac{4Z^2e^6}{m^2\omega}\left[\left(1+\frac{\varepsilon'^2}{\varepsilon^2}-\frac{2}{3}\frac{\varepsilon'}{\varepsilon}\right)\ln mR+\frac{\varepsilon'}{9\varepsilon}\right], \qquad (2.2)$$

where $Z|e|$ is the charge of atomic nuclear and R is the screening radius of atomic potential.

Moving in an amorphous medium electron sequentially interacts with different atoms of a medium, and these collisions can be considered as random. If the electron in limits of coherence length of radiation process collides only with one atom, then the interference of radiation from electron interaction with other atoms of a medium is unessential. Thus the radiation spectral density is determined by the formula [4,5]

$$\frac{dE_{BH}}{d\omega} = \frac{2L}{3L_{Rad}}\left[\left(1+\frac{\varepsilon'^2}{\varepsilon^2}\right)+\frac{\omega^2}{2\varepsilon^2}\right], \qquad (2.3)$$

where L_{Rad} is the radiation length,

$$L_{Rad}^{-1} = (4Z^2e^6n/m^2)\ln mR \qquad (2.4)$$

and n is the density of atoms in a medium.

Landau and Pomeranchuk showed in Ref. [3], that if in limits of coherence length of radiation process an electron interacts with a large number of atoms, the multiple scattering of particle on these atoms could conduce to suppression of bremsstrahlung in an amorphous medium. The effect of suppression of radiation arises, when the mean square angle of multiple scattering of a particle on atoms of a medium in limits of coherence length of the radiation process exceeds square of a characteristic angle of radiation of a relativistic electron $\theta_\gamma^2 \sim m^2/\varepsilon^2$. This result was obtained on the basis of the classical theory of electron radiation. However, the formula for a spectral density of electron radiation in substance, obtained by Landau and Pomeranchuk, has only evaluative character. The reason is that at the development of this formula the terms of the same order of smallness, as left ones were discarded. (This circumstance was noted in Refs. [9,14].)

The quantitative theory of the multiple scattering effect on an electron radiation in an amorphous medium was offered by Migdal in Ref. [24]. This theory was based on the application of the kinetic equation method to the given task. Migdal obtained the following formula for a spectrum of electron radiation in an amorphous medium at $\omega \ll \varepsilon$

$$\frac{dE}{d\omega} = \left(\frac{dE}{d\omega}\right)_0 \Phi_M(s), \qquad (2.5)$$

where $(dE/d\omega)_0$ is the spectrum of radiation without taking into account the multiple scattering influence on radiation (this value with a logarithmic accuracy coincides appropriate result of Bethe and Heitler (2.3)) and $\Phi_M(s)$ is the function, obtained by Migdal, and which describes the influence of multiple scattering on radiation

$$\Phi_M(s) = 24s^2\left(\int_0^\infty dx\, cth\, x\, e^{-2sx}\sin 2sx - \frac{\pi}{4}\right). \qquad (2.6)$$

The parameter s is determined by the expression

$$s = \frac{1}{2}\sqrt{\frac{\omega}{2\omega_{LPM}}}, \qquad (2.7)$$

where

$$\omega_{LPM} = \frac{16\pi\, Z^2e^4\varepsilon^2 n}{m^4}\ln(mR). \qquad (2.8)$$

The value ω_{LPM} determines the range of gamma quanta energies, starting with which the multiple scattering influences radiation spectrum essentially.

Owing to Migdal's important contribution to the theory of the given effect now it is called the Landau-Pomeranchuk-Migdal effect.

The function of Migdal is close to a unit at s ≥ 1, i.e. at $\omega \geq \omega_{LPM}$. The spectrum of radiation in this case coincides with the corresponding result of Bethe and Heitler.

If $s << 1$,

$$\Phi(s) \approx 6s\,. \tag{2.9}$$

The intensity of radiation in this case is much less, than the corresponding result of Bethe and Heitler.

The theory of the LPM effect has afterwards got its development in a number of works. In particular, on the basis of the method of density matrix the recoil effect at radiation was taken into account, the influence of polarization of a medium and boundaries of the target on radiation of photons and a number of other effects at high energy electrons and photons interaction with an amorphous medium were taken into account (see monographs and reviews [4,5,25,26] and references in them). All these researches are based on the application to the given task either the method of kinetic equation or the density matrix method.

3. THE LPM EFFECT IN AMORPHOUS MEDIA AND IN CRYSTAL

At the end of the 1970s there was a new interest to investigation of the LPM effect. It was stipulated by the analysis of processes of relativistic electrons interaction with crystals. There were several reasons for this. Let's point out only some of them.

Firstly, the analysis of applicability conditions of the Born theory results of coherent radiation of electrons in a crystal, carried out in the 1970s, has shown, that the condition of applicability of a Born approximation in the given task is destroys quickly with increase of energy and with decrease of the angle of particle falling on a crystal related to one of the crystal axes [5,6,9]. Thus, to describe the interaction of an electron with a crystal it was required to advance methods permitting to go beyond the frameworks of the Born perturbation theory. Such methods were developed on the basis of the classical theory of radiation, as well as the eikonal and quasi-classical approximation of a quantum electrodynamics. It indicated a possibility to consider the processes of particle radiation in crystals and in amorphous media from uniform positions (on the basis of identical methods) and to reveal common regularities and distinctive features between the processes of radiation of particles in these cases.

Secondly, the analysis of the process of scattering of charged particles in a crystal showed, that in case of special orientations of the latter, there can be set up the conditions, when the average value of scattering angles of particles will considerably exceed the corresponding value of scattering angles in an amorphous medium [8,9]. It indicated new possibilities for investigation of the LPM effect at interaction of particles with crystals. Research in this direction has led to the following results.

4. RADIATION IN A THIN LAYER OF SUBSTANCE

The analysis of the radiation process of a relativistic electron in a thin layer of substance has shown, that at rather high energies of electrons and small energies of radiated photons the following condition can be carried out [7,9]

$$l_c >> L\,, \tag{4.1}$$

e.g. the coherence length of radiation is greater, than the target thickness L. The process of radiation in this case was explicitly studied in [7,15-17,26]. It was shown, that at realization of the condition (4.1) the radiation spectral density is determined by the expression

$$\frac{dE}{d\omega} = \frac{2e^2}{\pi}\int d^2\vartheta\;\, f(\vartheta\,,L)\left[\frac{2\xi^{\,2}+1}{\xi\,\sqrt{\xi^{\,2}+1}}\,l\text{n}\left(\xi+\sqrt{\xi^{\,2}+1}\right)-1\right] \text{,} \tag{4.2}$$

where $\xi = \gamma\theta/2$, θ is the scattering angle of particles by the target and $f(\theta,L)$ is the distribution function of particles on angles θ.

The formula (4.2) shows that at realization of the condition (4.1) the radiation spectral density is determined only by the scattering angle of a particle and does not depend on details of its trajectory in a target. Therefore, the formula (4.2) can be used when studying radiation of particles, both in crystalline, and amorphous targets. The difference between processes of radiation in these cases will be determined only by distribution function of scattered particles on angles.

The formula (4.2) has simple asymptotes at small and large values of a mean square angle of multiple scattering of particles by the target $\overline{\vartheta^{\,2}}$:

$$\frac{dE}{d\omega} \approx \begin{cases} \dfrac{2e^2}{3\pi}\gamma^{\,2}\overline{\vartheta^{\,2}}, & \gamma^{\,2}\overline{\vartheta^{\,2}} << 1\,; \\ \dfrac{2e^2}{\pi}\ln(\gamma^{\,2}\overline{\vartheta^{\,2}})\,, & \gamma^{\,2}\overline{\vartheta^{\,2}} >> 1\,. \end{cases} \tag{4.3}$$

In the amorphous target the value $\overline{\vartheta^{\,2}}$ is proportional to the thickness L. Thus, if $\gamma^{\,2}\overline{\vartheta^{\,2}} << 1$, the formula (4.3) passes into the corresponding result of Bethe and Heitler (2.3). If $\gamma^{\,2}\overline{\vartheta^{\,2}} >> 1$, then according to (4.3), the linear dependence of $dE/d\omega$ from L is replaced by a weaker logarithmic one. It means, that at realization of the condition $\gamma^{\,2}\overline{\vartheta^{\,2}} >> 1$ the effect of suppression of radiation as contrasted to the corresponding result of Bethe and Heitler takes place.

Modification of character of electron radiation in a thin layer of substance happens under the same conditions, as in case of the LPM effect. However, the radiation spectral densities (2.5) and (4.3), essentially differ (different are the dependencies from L, ε and ω). It is connected that the formula (4.3) is valid at realization of the condition $l_c >> L$, whereas the formula (2.5), describing the LPM effect is valid at $l_c << L$.

The similar effects are also possible at electron radiation in a crystal. However, in a crystal there can be carried out the conditions, at which the mean square value of multiple scattering angles will be considerably larger, than in an amorphous target. Thus, if $\gamma^2\overline{\vartheta^2} << 1$, the formula (4.3) turns into the corresponding result of the theory of coherent radiation of relativistic electrons in a field of atomic strings of a crystal. At realization of the condition $\gamma^2\overline{\vartheta^2} >> 1$, accordingly to (4.3), there appears an effect of suppression of coherent radiation. Thus, modification of the character of electron radiation in a crystal can take place much faster, than in the amorphous target.

5. QUANTUM THEORY

The results of the classical theory of radiation in thin layers of substance were generalized afterwards in the case, when the effect of quantum recoil at radiation is essential [5,17,27]. Such research was carried out on the basis of the theorem of a factorization of cross-section of high energy electron radiation in an external field, according to which the cross-section of radiation could be represents as a product of radiation probability and elastic scattering cross-section of a particle in this field. Thus, the only cross-section of elastic scattering depends on the external field. This theorem is valid, if the coherence length of the radiation process is big as contrasted to the longitudinal size of the spatial region, in which the external field influences on a particle.

At rather high of electron energy this condition can be always carried out at its interaction with a thin layer of substance. Thus, all layer of substance is considered as uniform object, with which the electron interacts. The scattering of a particle is considered in an eikonal approximation of the quantum theory of scattering.

This approach allowed considering not only the process of radiation, but also such processes as a photo- and electro-production of electron-positron pairs at high energies in a thin layer of substance [9,17,27,28]. Thus, it was shown that for all these processes when the thickness of the target increases, the linear dependence of their cross-sections from the target thickness is replaced by a weaker logarithmic one. Modification of the character of these processes happens at realization of the same conditions, as in the case of the LPM effect. Such effect takes place at particles interaction with both an amorphous and crystalline targets.

When studying the process of scattering of high energy electrons in a thin layer of an amorphous substance in the eikonal approximation of the quantum theory of scattering the following result was also obtained [9,17,27,28]. It was shown, that the averaging of quantum cross-section of scattering by positions of atoms in the target leads to the angular distribution of scattered particles, which exactly coincides with the Bethe-Molierè distribution obtained as a result of the solution of kinetic equation for the angular distribution function of particles in a medium. In other words, the study of the scattering of fast particles in an amorphous medium on the basis of an eikonal approximation of the quantum theory of scattering and on the basis of the method of the kinetic equation leads to identical results for the angular distribution function of particles.

6. THE FUNCTIONAL INTEGRATION METHOD

In Refs. [6,9] at studying the process of coherent radiation of relativistic electrons in a crystal outside the domain of applicability of the Born perturbation theory, were investigated the possibilities to develop the method of description of relativistic electrons radiation in substance, proposed by Landau and Pomeranchuk [3]. This method was based on the classical theory of radiation of electrons in substance. Thus, the inaccuracy of the Ref. [3] was corrected, and there was obtained a common formula (see formula (2.4) of Ref. [9]) for the spectral density of radiation of a relativistic electron moving in an external field on the given trajectory. Both the field of a crystal lattice and the field of an aggregate of atoms of an amorphous medium can be considered as an external field. In the latter case the trajectory of a particle in a medium is random, therefore the radiation spectral density should be averaged by random trajectories of an electron in substance. Thus, it was noted, that the radiation density, being a subject to an average, represents a functional, which has the Gaussian form. The random process, to which the multiple scattering of an electron in an amorphous medium is connected, can be considered as the Gaussian process. It meant, that for realization of the averaging procedure the method of functional integration (also known as the method of integration over trajectories) could be utilized.

The implementation of this method in the task of description of the LPM effect was realized in [29-31]. Thus, on the basis of the method of functional integration it became possible to reproduce completely the main result of the Migdal theory. It opened new possibilities in describing the interaction of high energy particles with substance.

This method was also applied to the task on the influence of multiple scattering of high energy electrons on atomic strings of a crystal on the process of their coherent radiation in a crystal [29,31]. Thus, it was shown, that the multiple scattering of electrons in a crystal at high energies leads to suppression of the process of their coherent radiation. This effect is similar to the LPM effect in an amorphous medium. However, in a crystal, contrary to an amorphous medium, the coherent radiation is suppressed, and the conditions of the effect appearance could be fulfilled much earlier, than in an amorphous medium. It happens because the average value of angles of multiple scattering of electrons on atomic strings of a crystal could considerably exceed the average value of angles of multiple scattering of particles in an amorphous medium.

The substantiation of using of a method of a functional integration in the task about radiation of an electron in a crystal was based on dynamic chaos phenomenon at motion of a particle in periodic field of atomic strings of a crystal [32-34].

Afterwards on the basis of the functional integration method the spectral-angular distribution of bremsstrahlung of a high energy electron in an amorphous medium was researched [35]; the influence of polarization of a medium on radiation and the recoil effect at radiation were taken into account [5,36,37]; the process of electron-positron pair production in amorphous and crystalline mediums was surveyed [5,36]; the influence of multiple scattering on energy losses by fast charged particles in substance was investigated [5,38]. Recently in Ref. [39] there was shown a possibility of utilization of the method of functional integration in the task on the influence of multiple scattering of relativistic electrons in a crystal on the process of their parametric X-radiation as well.

7. EXPERIMENTAL RESEARCHES OF THE LPM EFFECT

The first experiments on detection of the LPM effect were conducted using of cosmic rays [40,41] and secondary electron beams with the energy of 40 GeV on the protons accelerator of IHEP (Protvino, Russia) [42]. Because of the insufficient statistics of measurements these experiments could only deal with qualitative confirmation of the LPM effect existence.

The detail experimental research of the LPM effect was carried out only recently, 40 years after its prediction. This experiment was carried out in 1993-95 on SLAC accelerator at the electron energies 8 and 25 GeV [10-13]. In this experiment there were measured the spectra of bremsstrahlung in the region of small energies of gamma-quanta (from 200 keV up to 500 MeV) for targets produced from different materials (from carbon to uranium) and in a rather wide interval of target thickness (from 0.1 % up to 6 % of radiation lengths).

The measurements were carried out with a rather high accuracy that allowed realizing a quantitative comparison of experimental data with theoretical calculations, and to research different mechanisms of medium influence on the process of bremsstrahlung of electrons in substance. Some results of the experiment and the comparison of experimental data with theoretical calculations are presented in Figs. 1-3.

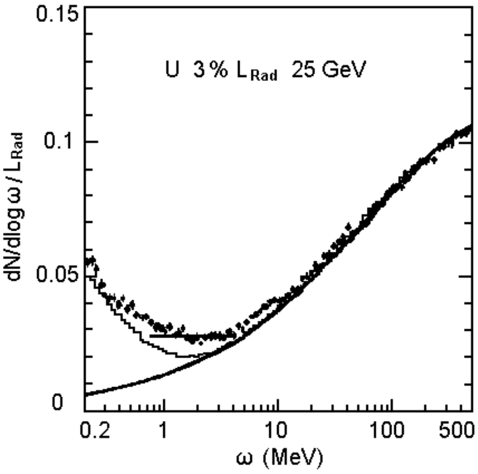


Fig. 1. *Radiation spectra of 25 GeV electrons in the uranium target of thickness 3% L_{Rad} in the range of photon energies from 200 keV to 500 MeV*

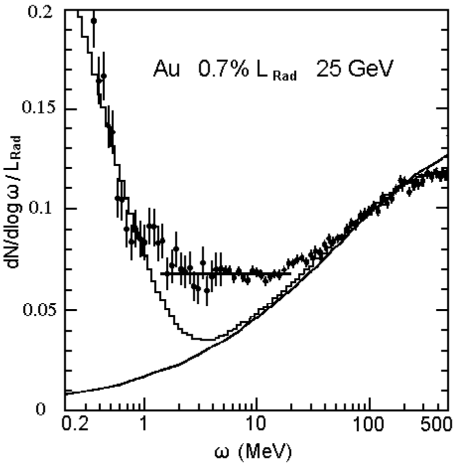


Fig. 2. *The same as in Fig. 1, for the golden target of thickness 0.7% L_{Rad}*

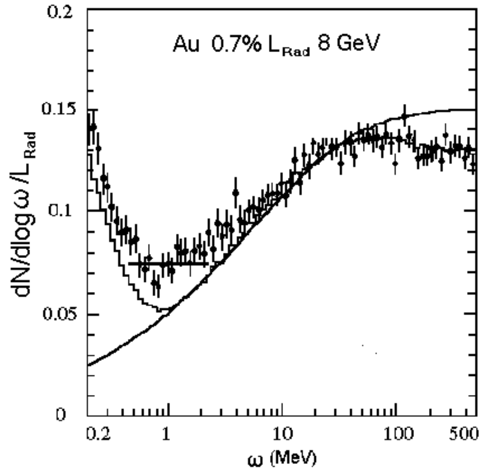


Fig. 3. *The same as in Fig. 2, for 8 GeV electrons*

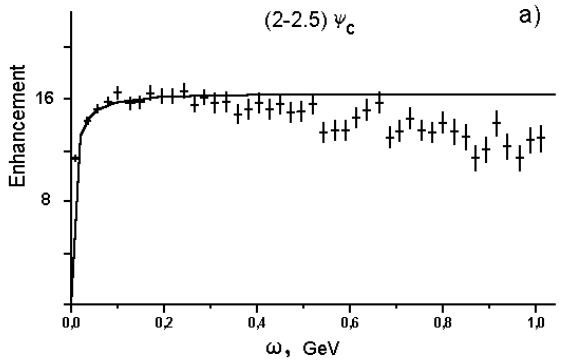
The solid curves in these figures correspond to the results of calculations under the Migdal's formula Eq. (2.5), histograms are the results of the Monte-Carlo simulation of radiation spectrum in Refs. [12,13], straight lines are the results of calculations under the Eq. (4.2).

The experimental data obtained in SLAC have shown not only a good consent with predictions of the Migdal theory for rather thick targets, but also a considerable discrepancy with the latter in the case of targets of relatively small thickness. The experiment carried out in SLAC boosted further development of the theory of multiple scattering influence on bremsstrahlung of relativistic electrons in substance permitting to take into account the finiteness of the target sizes and its structure [14,16-22,43]. The analysis of the results of this experiment showed, that, alongside with confirmation of the LPM effect, the effect of suppression of bremsstrahlung of high energy electrons in a thin layer of substance was also confirmed. This effect was pointed out in Refs. [7,44].

In the 1980s detailed research of the process of radiation of electrons and positrons with energies from several GeV up to several tens GeV in the aligned crystals were carried out. Such researches were conducted on accelerators SLAC (Stanford), KIPT (Kharkov), YerPI (Yerevan), TPI (Tomsk), IHEP (Protvino), CERN (Geneva). The main attention in these experiments was paid to the research of radiation properties of particles moving under the conditions of planar and axial channeling and above-barrier motion relative to the crystalline planes of atoms and atomic strings of a crystal. In some experiments the spectra of radiation at disorientation of a crystal on some values of a critical angle of an axial channeling were obtained. One of the purposes of these experiments was to research the influence of multiple scattering of particles in crystals on the process of their coherent radiation. Of special interest is the experiment [45], in which the attempt to detect the effect of suppression of coherent radiation similar to the LPM effect was undertaken. The experiment was carried out on electron beams with the energy 10 GeV and positrons with the energy 10 and 20 GeV at disorientation of an axis <110> of a silicon crystal on angles up to ten critical angles of an axial channeling ψ_c [45]. Some results of this experiment and the corresponding theoretical curves are presented in Figs. 4,5.

The ration of radiation spectral density in a crystal to the corresponding value in an amorphous medium is put on the axis of ordinates. The experimental data are obtained by averaging the spectrum of radiation over azimuthal angles as related to the axis <110> (see Fig. 17 in Ref. [45]).

The results of the experiment show that in the region of high energies of radiated gamma-quanta (ω > 200 MeV) the spectra of radiation slightly depend on the energy of a gamma-quantum. The value of emission intensity in this range of frequencies coincides with the corresponding result of the theory of coherent radiation of relativistic electrons in a crystal obtained in an approximation of random collisions of a particle with atomic strings. In the range of relatively small energies of emitted quanta (ω < 200 MeV) the effect of suppression of coherent radiation takes place, and theoretical predictions in this range of frequencies are also in a rather good consent with the experiment [46].



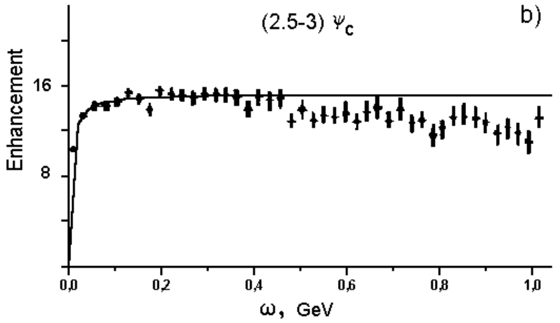


Fig. 4. The radiation spectra of electrons with energy 10 GeV arriving at a silicon crystal at small angles ψ to the axis <110>: the dots correspond to experimental data from Ref. [45]; the solid lines show the results of calculations from Ref. [46]. The intervals of angles ψ, for which the measurements were carried out, are shown in the figure: a) $\psi = (2 - 2.5)\psi_c$ and b) $\psi = (2.5 - 3)\psi_c$

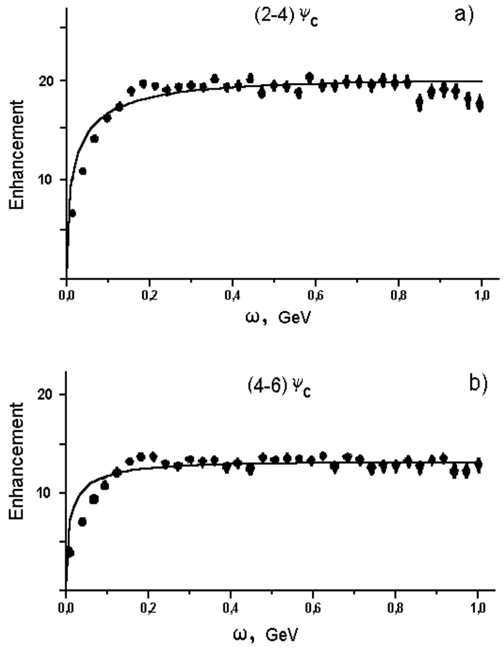


Fig. 5. The same as in Fig. 4, for 20 GeV positrons a) $\psi = (2 - 4)\psi_c$ and b) $\psi = (4 - 6)\psi_c$

This effect of suppression of coherent radiation is similar to the LPM effect of suppression of bremsstrahlung in an amorphous medium. The experiment also shows, that in a crystal the effect of suppression of coherent radiation occurs much earlier than in an amorphous medium (in the case of amorphous targets of carbon and aluminum, as shown in the experiment [12] for 25 GeV electrons the LPM effect arises in the region of gamma quanta energies about several tens MeV).

In conclusion we shall note, that the multiple scattering of electrons on atomic strings of a crystal can also lead to suppression of coherent radiation at electron energies of about several hundreds MeV, when the condition of dipole radiation of particles in a crystal is satisfied, i.e. at realization of the condition $\overline{\vartheta^2} < \gamma^{-2}$ [26,31,47]. However, the mechanism of this effect emergence differs from the mechanism of the LPM effect. The given effect has not been experimentally investigated yet.

ACKNOWLEDGMENTS

The work was partially supported by the Science and Technology Center in Ukraine (project №1746).

REFERENCES

1. N.F. Shul'ga. High-energy quantum Electrodynamics in matter // *Ukr. Journ. of Phys.* 1998, v. 43, p. 1032-1037.
2. N.P. Dikiy, A.N. Dovbnya, I.I. Zalubovsky, R.P. Slabospitsky, P.V. Sorokin, N.F. Shul'ga. Studies on high energy physics, nuclear physics and electron linear accelerators // *Ukr. Journ. of Phys.* 1998, v. 43, № 9, p. 1108-1126.
3. L.D. Landau, I.Yu. Pomeranchuk. Electron-cascade processes at ultra-high energies // *Dokl. Akad. Nauk SSSR*. 1953, v. 92, p. 735-740 (in Russian).
4. M.L. Ter-Mikaelian. *High-energy electromagnetic processes in condensed matter.* New York: "Wiley Interscience", 1972, 457 p.
5. A.I. Akhiezer, N.F. Shul'ga. *High-energy electrodynamics in matter.* Amsterdam: "Gordon and Breach", 1996, 388 p.
6. A.I. Akhiezer, V.F. Boldyshev, N.F. Shul'ga. Theory of elastic scattering and bremsstrahlung of fast charged particle in crystals // *Sov. J. Particles and Nuclei.* 1979, v. 10, p. 51-89.
7. N.F. Shul'ga, S.P. Fomin. On suppression radiation effect in amorphous media and crystals // *JETP Lett.* 1978, v. 27, p. 117-120.
8. N.F. Shul'ga, V.I. Truten', S.P. Fomin. On multiple scattering of relativistic particles in crystals // *Sov. Phys. – Techn. Phys.* 1982, v. 27, p. 1399-1400.
9. A.I. Akhiezer, N.F. Shul'ga. Radiation by relativistic particle in crystal // *Sov. Phys. Uspekhi.* 1982, v. 25, p. 541-564.
10. R.L. Anthony, R. Backe-Szendy, P. Bosted et al. An accurate measurement of the Landau-Pomeranchuk-Migdal effect // *Phys. Rev. Lett.* 1995, v. 75, p. 1949-1952.
11. R.L. Anthony, R. Backe-Szendy, P. Bosted et al. Measurement of dielectric suppression of bremsstrahlung // *Phys. Rev. Lett.* 1996, v. 76, p. 3550-3553.
12. R.L. Anthony, R. Backe-Szendy, P. Bosted et al. Bremsstrahlung suppression due to the Landau-Pomeranchuk-Migdal and dielectric effects in a variety of materials // *Phys. Rev.* 1997, v. D56, p. 1373-1390.
13. S. Klein. Suppression of bremsstrahlung and pair production due to environmental factors // *Rev. of Mod. Phys.* 1999, v. 71, p. 1501-1538.
14. R. Blankenbacler, S.D. Drell. The Landau-Pomeranchuk-Migdal effect for finite targets // *Phys.Rev.* 1996, v. D53, p. 6265-6281.
15. S.P. Fomin, N.F. Shul'ga. On the space-time evolution of the process of ultra relativistic electron radiation in a thin layer of substance // *Phys. Lett.* 1986, v. A114, p. 148-152.
16. N.F. Shul'ga, S.P. Fomin. Multiple scattering effect on radiation by ultra relativistic electron in a thin layer of mater // *JETP.* 1998, v. 86, p. 32-38.
17. N.F. Shul'ga, S.P. Fomin. Bremsstrahlung of ultra relativistic electrons in a thin layer of mater // *Nucl. Instr. Methods*. 1998, v. B145, p. 180-184.
18. R. Blankenbacler. Structured targets and Landau-Pomeranchuk-Migdal Effect // *Phys. Rev.* 1997, v. D55, p. 190-195.
19. B.G. Zhakharov. Structured targets and Landau-Pomeranchuk-Migdal effect for finite-size targets // *JETP Lett.* 1996, v. 64, p. 781-787.
20. B.G. Zhakharov. Light-cone path integral approach to the Landau-Pomeranchuk-Migdal effect // *Yadernaya Fiz.* 1998, v. 61, p. 924-940.
21. R. Baier, Yu.L. Dokshitser, A.H. Mueller, S. Peigne, D. Schiff. The Landau-Pomeranchuk-Migdal effect in QED // *Nucl. Phys*. 1996, v. B478, p. 577-597.
22. V.N. Baier, V.M. Katkov. Landau-Pomeranchuk-Migdal effect and transition radiation in structured targets // *Phys. Rev.* 1999, v. D60, 076001, 12 p.
23. A.I. Akhiezer, V.B. Berestetskii. *Quantum Electrodynamics*. New York - London: "Wiley-Interscience, 1965.
24. A.B. Migdal. The influence of the multiple scattering on the bremsstrahlung at high energies // *Dokl. Akad. Nauk SSSR.* 1954, v. 96, p. 49-52 (in Russian).
25. M.I. Riazanov. Bremsstrahlung and pair production at ultra high energies in condensed amorphous media // *Usp. Phys. Nauk.* 1974, v. 114, p. 393-415 (in Russian).
26. A.I. Akhiezer, N.F. Shul'ga. The effect of multiple scattering on relativistic particle radiation in amorphous and crystal media // *Sov. Phys. Uspekhi*. 1987, v. 30, p. 197-218.
27. A.I. Akhiezer, N.F. Shul'ga. Semiclassical theory of high energy particle radiation in external fields // *Physics Reports.* 1993, v. 244, p. 297-365.
28. A.I. Akhiezer, S.P. Fomin, N.F. Shul'ga, V.I. Truten'. Coherent effect in electron-positron pair production in crystals // *Dokl. Akad. of Science of SSSR.* 1979, v. 249, p. 338-341.
29. N.V. Laskin, A.S. Mazmanishvili, N.F. Shul'ga. Continual method in the problem of multiple scattering effect on radiation by high energy particle in amorphous media and crystals //

Dokl. Akad. of Science of SSSR. 1984, v. 277, p. 850-853.
30. N.V. Laskin, A.S. Mazmanishvili, N.F. Shul'ga. A method of path integration and Landau-Pomeranchuk effect of suppression of fast particle radiation in matter // *Phys.Lett.* 1985, v. A112, p. 240-242.
31. N.V. Laskin, N.N. Nasonov, A.S. Mazmanishvili, N.F. Shul'ga. Theory of radiation by relativistic particles in amorphous media and crystals // *JETP.* 1985, v. 62, p. 438-447.
32. Yu.L. Bolotin, V.Yu. Gonchar, V.I. Truten', N.F. Shul'ga. Channeling and dynamical chaos // *Ukr. Phys. Journ.* 1986, v. 31, p. 14-16.
33. Yu.L. Bolotin, V.Yu. Gonchar, V.I. Truten', N.F. Shul'ga, Dynamical chaos in the motion of fast particles through a crystals // *Phys.Lett.* 1987, v. A123, p. 357-360.
34. A.I. Akhiezer, N.F. Shul'ga, V.I. Truten'. Dynamical chaos in the motion of charged particles through a crystals // *Physics Reports*. 1991, v. 203, p. 289-343.
35. N.V. Laskin, A.I. Zhukov. Angular characteristic of the radiation emitted by relativistic electrons in matter // *JETP.* 1990, v. 98, p. 571-583.
36. A.I. Akhiezer, N.V. Laskin, N.F. Shul'ga. Method of functional integration in quantum theory of radiation by fast charged particles in matter // *Dokl. Akad. of Science of SSSR.* 1987, v. 295, p. 1363-1365.
37. A.I. Akhiezer, N.V. Laskin, N.F. Shul'ga. On recoil effect in radiation by relativistic particles // *Dokl. Akad. of Science of SSSR*. 1988, v. 303, p. 78-81.
38. A.I. Akhiezer, N.V. Laskin, N.F. Shul'ga. Multiple scattering effect on energy losses of fast charged particles in matter // *Dokl. Akad. of Science of SSSR.* 1987, v. 295, p. 95-97.
39. N.F. Shul'ga, M. Tabrizi. Multiple scattering effect on the line width of Parametric X-Ray relativistic radiation in a crystal // *JETP Lett*. 2002, v. 76, p. 279-282.
40. M. Miesowicz, O. Stanisz, W. Wolther. Investigation of an electromagnetic cascade of very high energy in the first stage of its development // *Nuovo Cimento*. 1957, v. 5, p. 513-516.
41. A. Varfolomeev, R.R. Gerasimova, I.I. Gurevitch et al. Influence of the medium density on bremsstrahlung in electron-photon showers in the energy range 10^{11}-10^{13} eV // *Sov. Phys. JETP.* 1960, v. 38, p. 33-45.
42. A. Varfolomeev et al. Effect of the medium on the bremsstrahlung spectra of 40 GeV electrons // *Sov. Phys. JETP.* v. 69, p. 429-438.
43. N.F. Shul'ga, S.P. Fomin. On experimental verification of the Landau-Pomeranchuk-Migdal effect // *JETP Lett.* 1996, v. 63, p. 873-877.
44. F.F. Ternovskii. On the theory of radiative processes in piecewise homogeneous media // *Sov. Phys. JETP.* 1961, v. 12, p. 123-130.
45. J.F. Bak, J. Ellison, B. Marsh et al. Channeling radiation from 2 to 20 GeV/c electrons and positrons // *Nucl. Phys*. 1988, v. B302, p. 525-558.
46. N.V. Laskin, N.F. Shul'ga. Effect of multiple scattering on coherent radiation of fast particles in crystals // *Phys. Lett.* 1989, v. A135, p. 147-149.
47. N.F. Shul'ga, V.I. Truten'. Coherent radiation from relativistic electrons in oriented crystal // *In the book "Electron-photon Interaction in Dense Media" (Ed. H. Wiedemann).* Kluwer Acad. Publ. 2001, p. 197-210.