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The Mechanism of Vavilov–Cherenkov Radiation

"When, in around 1860, the law of conservation of energy was eventually generally recognized, it very quickly became a cornerstone of the whole of natural science. Since then any new theory, especially a physical one, has been above all evaluated with respect to its agreement with the law of conservation of energy."

M. Laue, "*Inertia and Energy*," *Sov. Phys. Uspekhi*, vol. LXVII, issue 4, p. 729 (1959).

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Abstract—The mechanism of generation of Vavilov–Cherenkov radiation is discussed in this article. The developers of the theory of the Vavilov–Cherenkov effect, I.E. Tamm and I.M. Frank, attributed this effect to their discovery of a new mechanism of radiation when a charged particle moves uniformly and rectilinearly in the medium. As such a mechanism presupposes the violation of the laws of conservation of energy and momentum, they proposed the abolition of these laws to account for the Vavilov–Cherenkov radiation mechanism. This idea has received a considerably wide acceptance in the creation of other theories, for example, transition radiation theory. In this paper, the radiation mechanism for the charge constant motion is demonstrated to be incorrect, because it contradicts not only the laws of conservation of energy and momentum, but also the very definitions of uniform and rectilinear motion (Newton's First Law). A consistent explanation of the Vavilov–Cherenkov radiation microscopic mechanism that does not contradict the basic laws is proposed. It is shown that the radiation arises from the interaction of the moving charge with bound charges that are spaced fairly far away from its trajectory. The Vavilov–Cherenkov radiation mechanism bears a slowing down character, but it differs fundamentally from bremsstrahlung, primarily because the Vavilov–Cherenkov radiation onset results from a two-stage process. First, the moving particle polarizes the medium; then, the already polarized atoms radiate coherently, provided that the particle velocity exceeds the phase speed of light in the medium. If the particle velocity is less than the phase speed of light in the medium, the polarized atoms return energy to the outgoing particle. In this case, radiation is not observed. Special attention is given to the relatively constant particle velocity as the condition of the coherent composition of waves. However, its motion cannot be designated as a uniform and rectilinear one in the sense of its definition by Newton's First Law, and it also contradicts the laws of conservation of energy and momentum.

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1. INTRODUCTION

More than 70 years have passed since the macroscopic theory of the Vavilov–Cherenkov effect [1] was developed. In the course of these years, a great number of different studies have been carried out in this field and hundreds of experimental and theoretical works have been published, various types of Cherenkov counters have been successfully run in many laboratories all over the world, and several reviews and monographs have been written [2–5]. The Nobel Prize was awarded for the discovery of this phenomenon, but a correct account for the microscopic mechanism of Vavilov–Cherenkov radiation (VCR) generation has yet to be proposed. Many publications have categorically asserted things that obviously contradict basic laws. Weak attempts to make the explanation of the VCR mechanism conform with the fundamental laws have been made, but they have yet to gain wide acceptance. Usually, authors restrict themselves to concise remarks from which a reader is supposed to infer that everything is clear. However, most authors of various publications present incorrect accounts of the VCR mechanism.

Thus, for example, in his 1958 Nobel speech, Tamm [6] said, "for many decades, all young physicists were taught that light (and electromagnetic waves in general) can be produced only by *nonuniform motions of electric charges*. When proving this theorem, one has—whether explicitly or implicitly—to make use of the fact that super-light velocities are forbidden by the theory of relativity (according to this theory, no material body can ever even attain the velocity of light). Still, for a very long time the theorem was considered to have an unrestricted validity.

"So much so, that I. Frank and I, even after having worked out a mathematically correct theory of

Vavilov–Cherenkov radiation, tried in some at present incomprehensible way to reconcile it with the maxim about the indispensability of acceleration of charges."[1]

As early as in 1944, Tamm and Frank spoke about the subject of the incorrect training of "all young physicists" more definitely [7]. They claimed, "we note, incidentally, that, in the case of $v < c$, the law of conservation of energy does not equally allow both a single photon emission and simultaneous emission of a group of photons. However, for superluminal speed, such processes of higher order are possible and, moreover, condition (4) apparently is not obligatory for such processes."[2] Thus, in [7], to account for VCR mechanism, the law of conservation of energy was downplayed in the most unambiguous manner, this fact finding its confirmation in subsequent publications of numerous authors until the present time."

For instance, in M.A. Ter-Mikaelyan's book *High-Energy Electromagnetic Processes in Condensed Media* [8], on p. 210, the author states, "in most of the cases elaborated below, the particle velocity will be assumed to be constant. Proceeding from the laws of conservation of energy and momentum, it can be shown that a uniformly moving particle in the homogeneous medium does not emit electromagnetic waves (see the example at the end of §23). An exception to this rule is *superluminal electron* emission—the so called Vavilov–Cherenkov radiation, the theory of which was presented in the work of Tamm and Frank." Hence, Ter-Mikaelyan also excluded the laws of conservation of energy and momentum from the VCR mechanism, although while making reference to Nobel Prize winners.

The here-cited quotation from Ter-Mikaelyan's book [8] was taken from Chapter 6, "The Transition Radiation." Although the authors of the transition radiation theory, V.L. Ginzburg and Frank [9], also insist on its onset when the charge moves constantly, and thus they reject the laws of conservation of energy and momentum for any velocities of the moving charge, Ter-Mikaelyan does not extend the exclusion to the laws of conservation of energy and momentum to this phenomenon.

He extracted himself from this difficult situation in the following manner. On the same page [8], we read, "thus, excluding when radiation of a *superluminal* electron takes place, a uniformly moving particle does not emit electromagnetic waves passing through homogeneous medium. For the radiation to arise, it is necessary to create irregularity in the medium passed through by the particle. The most simple irregularity is the interface between the two homogeneous media." The author preferred not to clear up such details as whether irregularity modifies the particle motion character or the particle continues its constant motion when irregularity is present.

No questions arise when Ter-Mikaelyan writes that "the particle velocity will be assumed constant"; such a technique is often used. One cannot but agree with him when he states that the laws of conservation of energy and momentum do not allow the radiation of the constantly moving particle. Indeed, if a charged particle interacts with charges of a medium while moving through it, then such motion is not free and cannot be called uniform and rectilinear.

Strictly speaking, the laws of conservation of energy and momentum never permit radiation of a uniformly and rectilinearly moving particle at all. If we nevertheless listen to Laue's opinion cited as an epigraph to this article, the new theory needs to be corrected, rather than to state that it allows violations of the laws of conservation of energy and momentum. However, Laue's position is ignored by many authors, and denial of the law of conservation of energy is already becoming increasingly widespread.

Here is, for example, what one could read in the book by Ginzburg and V.N. Tsitovich [10]. In the very beginning of the chapter (p. 7) "Radiation of the Uniformly and Rectilinearly Moving Charge," the authors made a program statement that actually sums up the development of modern studies of the motion of charges: "in the course of many years, electrodynamics was dominated by a dogma that could be formulated in this way: a uniformly and rectilinearly moving charge does not radiate. Actually, a more precise definition should be given to such a statement, even for the case of the charge motion in vacuum (see below, and [1], Ch. 1). As for motion with constant velocity of the source without natural frequency (a charge, a constant dipole, etc.) in the medium or close by the medium, then radiation onset could be even considered not as an exception, but as a rule."

Thus, if Tamm and Frank had discarded the laws of conservation of energy and momentum only for superluminal velocities of moving charges [7], then Ginzburg and Tsitovich assert that the law that in Laue's opinion had been a "cornerstone of the whole of natural science" since 1860 fell from favor as early as in 1984 in the construction of new physical theories. Not only Ginzburg and Tsitovich consider the direct consequences from this law to be a dogma; Tamm calls the law a theorem, and Ter-Mikaelyan regards it as a rule from which he immediately makes an exception. This view is agreed upon by almost all authors of publications on VCR and transition radiation, although opposite approaches sometimes occur.

Thus, for instance, in the earlier work of Ginzburg [11], where he is reputed to be a developer of the quantum theory of VCR, in 1940 he used laws of conservation of energy and momentum for this theory con-

[1] This quotation was not translated from the manuscript, but was taken from the original Nobel lecture.

[2] Condition (4) is $\cos\Theta = c/vn$, where c is the speed of light in vacuum, v is the particle velocity, n is the refractive index, and Θ is the radiation angle.

struction. Assuming that VCR quantum is emitted directly by a moving charged particle, he obtained an expression for the radiation angle with correction for particle velocity variation both for the value and for the direction. Although the velocity variation was insignificant, in the article the author did not call the particle motion constant. What is more, in 1940 Ginzburg declared that the "classical calculation is being conducted with the supposition of the electron velocity constancy," in spite of the statement of the authors of the classical theory, Tamm and Frank [1], who as we have seen positively insisted on the uniform and rectilinear motion of the charge that generates the VCR. However, in the title of the article [11], Ginzburg still called the motion of the charge, which emits a quantum and varies its velocity by value and direction, uniform.

If in the calculation [11] only constant motion is supposed, then young physicists realized that in 1940 Ginzburg did not discard the laws of conservation of energy and momentum and did not call the direct consequence from them a dogma, as was done by Ginzburg and Tsitovich in [10] in 1984.

In the course of the time elapsed since the first explanation of VCR mechanism was given in the work of Tamm and Frank [1], with the assumption that the charge moving uniformly and rectilinearly in the medium radiates, some young physicists advanced in age and other young physicists are still trying to catch onto the VCR mechanism, but unfortunately famous scientists continue to impose on them a incorrect interpretation of the VCR mechanism.

For example, in 1996 S.P. Denisov, in a review lecture on the VCR [12], explained, "it is natural to ask: how can that be? Is it not that before Tamm and Frank's work was published in 1937, it was considered that a charge that moves with constant velocity cannot radiate. Yes, it was so considered. But therewith it was tacitly assumed that the charge velocity cannot exceed the speed of light propagation. But the latter is true for vacuum only. Really, according to relativity theory, the speed of light propagation $\mathbf{c} = 3 \times 10^8$ m/s is the maximum speed, and always $\mathbf{v} < \mathbf{c}$, where $\mathbf{v}$ is the velocity of the charge motion. Matter is something else. As is well known, in matter with refractive index $\mathbf{n}$, the speed of light equals $\mathbf{c}/\mathbf{n}$ and the condition $\mathbf{v} > \mathbf{c}/\mathbf{n}$ is feasible without contradicting relativity theory." Students hardly considered an answer convincing. The respected professor failed to provide any arguments as to why the laws of conservation of energy and momentum should be rejected with the condition $\mathbf{v} > \mathbf{c}/\mathbf{n}$.

In a lecture on transition radiation [13], Denisov once more turns to this problem: "is it possible for a constantly moving charge to emit electromagnetic waves? The overwhelming majority of higher school graduates answer this question categorically negatively. They explain: only a charge that moves with acceleration radiates. In the general case this answer is not correct. It is only true for a charge in vacuum. If the charge moves in matter with a constant velocity that exceeds the phase speed of light propagation in this substance, then Cherenkov radiation arises.

"But can a charge that moves without acceleration with a subluminal velocity radiate?"

Further on, a brief account of the transition radiation theory and the following generalization are given: "in general, if a uniformly and rectilinearly moving charge radiates in a laboratory system of coordinates, then the radiation will exist in any other frame of reference, including the one where a charge is at rest."

Higher school graduates are somewhat puzzled by this, as they were taught by M.V. Lomonosov that "if somewhere, something, and so many were subtracted, then as many will be added in some other place." They understand that a charge at rest simply does not have energy to radiate, but the respected professor maintains the opposite. Moreover, here already one cannot get by with a reference to relativistic velocity if a charge is at rest. Lomonosov seemingly is wrong, but if so his error must be explained. Such explanations were not presented.

All these references to "higher school graduates" and "young scientists" that the Nobel Prize winners never managed to convince in the course of 70 years are needed, because even the authors themselves doubt explanations of this sort. Thus, questions are being addressed to the "higher school graduates" and "young scientists" who have to uphold the basic laws. However, the fact that the very term "uniform rectilinear motion" is clearly defined by Newton's First Law has been noted by nobody so far, to the best of my knowledge. Everybody certainly knows this law, but here it is absolutely necessary to give its formulation. Newton's First Law reads: "every body continues in its state of rest or of uniform motion in a straight line untill and unless acted by an external force." [14].

Obviously, Newton's First Law makes it absolutely clear that a uniformly rectilinearly moving particle cannot interact in any manner with anything (particle, field, medium, interface), but if interaction with something occurs, then the particle transits to another state of nonuniform motion. If radiation is observed while the particle moves, then it is interacting with something and therefore is moving nonuniformly. Moreover, as is seen from the essence of this law, quantitative evaluations of deceleration do not matter, i.e., a charge cannot move "almost uniformly and rectilinearly," but only uniformly and rectilinearly or nonuniformly. As another definition for the uniform and rectilinear motion does not exist, then Newton's First Law cannot be rejected, even with reference to relativity theory. Hence, it is clear that the conception of uniform and rectilinear motion in Newton's definition is not compatible with modern interpretations of mechanisms of the transition radiation and VCR generation.

An arrangement of accelerators along the trajectory of the particle to keep its speed constant, as some authors propose [11], obviously cannot bring it to a state of uniform and rectilinear motion, but rather confirms its nonfree motion.

Thus, insisting on the radiation mechanism when the charge moves uniformly and rectilinearly, one is forced to discard both the laws of conservation of energy and momentum and Newton's First Law. The most surprising thing is that the developers of the new theories have not presented any serious arguments in favor of such an important step, but they propose to discard the basic laws.

Meanwhile, there is no necessity at all to discard the basic laws. From the aforesaid, it is absolutely evident that the generation mechanism of the VCR and the transition radiation can be only a decelerating one. The mechanism of VCR generation has of course essential features that considerably distinguish it from the bremsstrahlung mechanism, but these peculiarities can be explained in the framework of the basic laws. The energy spent on radiation by moving in the medium charge makes up a small part of its kinetic energy. Radiation is observed at all angles strictly symmetrically relative to the particle trajectory. These cases give rise to incorrect discussions about the radiation of a charge that moves uniformly and rectilinearly, thus violating the basic laws.

Here it is appropriate to recall, that many authors discussing the VCR mechanism draw an analogy to another phenomenon, but this time an acoustical one. It is interesting that nobody undertakes to assert that airplanes with supersonic speed move uniformly and rectilinearly and do not follow the laws of mechanics.

The reader has probably already posed the question "If the author of this article sees all these contradictions, then why in the course of 70 years has nobody seen them ?" I answer, "People have seen and written on this subject more or less definitely, but their opinion was fully ignored in all publications on VCR and transition radiation."

For instance, the position of Enrico Fermi still remains without proper attention. In [15] he stated the following: "such an emission of radiation has actually been observed by Cerenkov, and can easily be seen to occur in those ranges of frequency for which the phase velocity of light in the given medium is smaller than the velocity of the particle. Its theory has been developed by Frank and Tamm with methods very similar to those used here and with similar results. It is noteworthy that the Cerenkov radiation, as results from the preceding formulae, *does not represent a loss of energy to be added to that calculated with the Bohr theory; but it forms instead part of loss of the Bohr theory*, as is seen from the fact that (30) (31), which include the Cerenkov radiation, give the same result (32) as the Bohr theory in the limit of very low densities ($\varepsilon = 1$) when the polarization effects become negligible."[3]

[3] The author of the Russian manuscript cites [15] in the original.

As we see, Fermi states that the VCR mechanism corresponds to the Bohr theory, i.e., that related to the decrease of velocity. Moreover, the idea that he disproves (another non-Bohr, nonstopping mechanism) obviously arose after Fermi had become acquainted with the daring statements of the developers of the VCR theory, Tamm and Frank, that were adduced in their fundamental work [1]. One cannot but agree with Fermi's remark, because in the opposite case it turns out that an incident charge interacts with medium atoms twice: first, according to the stopping mechanism, and, second, following the new VCR mechanism. Fermi, however, did not explain to what extent the mechanism of VCR generation differs from the ordinary bremsstrahlung mechanism and what the essence of the difference is.

Tamm and Frank, when studying Fermi's work [15], paid no attention to his remark regarding the VCR mechanism. This can be seen in the following comment [7]: "in close collisions, a moving electron transfers so great an energy to the electrons of the medium that these electrons can be considered free. As for distant collisions with small energy transfers, the energy and optical spectrum of the medium atoms play a considerable role. Until now, when considering distant collisions, it was not taken into account that the electric field of the moving electron that affects distant (compared with interatomic spacing) atoms of the medium by no means coincides with the field of this electron in vacuum, but undergoes a modification due to the medium presence. This circumstance was pointed at by Fermi [56], who developed a new theory of ionization loss that is free of this shortcoming, with significant results for the theory of cosmic rays. Fermi took into account the effect of the medium on the moving electron field, using a method quite analogous to the method applied in the VCR theory by the authors of this article, whose first report [4] Fermi refers to in connection with the problem considered."

Another author, O. Bohr still insists on the importance of Fermi's critical remark. In the supplement to Niels Bohr's book [16] *The Penetration of Atomic Particles through Matter* in part 7, "The Cherenkov Effect and Its Relation with the Problem of Decrease of Velocity," he writes, "in the present part we will discuss some features of the Cherenkov effect, in particular its connection with the theory of the decrease of velocity. Considering the effect both from the microscopic and the macroscopic points of view is of interest. In the first case, we will obtain a direct connection with the debates of part 6, while the second standpoint is analogous to that developed by Tamm, Frank, and Fermi.

"From the microscopic point of view, the Cherenkov effect arises because part of the energy transferred by the penetrating particle can be subsequently emitted as coherent radiation. In the previous part, there was no necessity to take this effect into account, because, in the problem of a stopping power one should consider in the first approximation the behavior of the electron only at the time instant of the collision with a particle. It is indeed possible to say that the particle loses energy during this short period of time and is not affected by further distribution of energy transferred to the electron. For these reasons, it becomes obvious that the Cherenkov effect conforms to the part of stopping power that was evaluated in section 6 and should not be considered as an additional source of energy losses (see Fermi [6]."

In Bohr's book and the supplement written by O. Bohr, the interaction of a moving charge with one at rest and the interaction of a moving charge with an isolated atom and with atoms in a solid were considered in every detail, including the effects connected with VCR. Moreover, the authors did not allocate the mechanism of the VCR generation as a special phenomenon, but on the contrary they offered it as a variant of electromagnetic interaction between charges. Abolition of the laws of conservation of energy and momentum is out of the question, as the final result of their research is the calculation of the charge energy loss when moving in a medium.

However, in book of G.M. Garibyan and Yan Shi [17], one can find such an explanation of the VCR mechanism. They explain the VCR and the transition radiation mechanism as follows: "the fact that Vavilov–Cherenkov radiation and the transition radiation are described by one and the same formula (1.37) (in the more general case, (1.35)) is not accidental. The point is that both these radiations take place when the charged particle moves uniformly and rectilinearly (or, in other words, within the limit of the infinite rest mass of the particle), and thus both of them represent the electron collective radiation in the medium where electrons experience recoil when interacting with an incoming external charge. In this sense, these two types of radiation cannot be considered different in principle and their division bears a somewhat conditional character."

The authors had found a remarkable formulation, which, on one the hand, almost exactly coincides with the already classical one (it takes place with uniform and rectilinear motion), but in parentheses have added a remark about a particle with infinite rest mass, which shows that real particles move quite nonuniformly when exciting the VCR. If one recalls that the developers of the theory of VCR and transition radiation usually considered a moving electron, not a particle with infinite rest mass, then the hint at the "slightly nonuniform motion" becomes absolutely transparent. After talking a little about how uniform the particle motion in the medium is, the authors of [17] nevertheless confirm that "the group of electrons in the medium" emits the energy transferred to it, which is close to the explanation proposed by O. Bohr [16]. Still, O. Bohr's objection to the developers of the VCR theory regarding the stopping character of the radiation mechanism was left by Garibyan and Yan Shi without attention.

The question of the particle mass tending to infinity is also discussed in book by L.D. Landau and E.M. Lifshitz [18], but here the authors somewhat shifted the accent: "the charged particle that moves in a transparent medium under certain conditions emits a peculiar radiation; it was first observed by S.I. Vavilov and P.A. Cherenkov and was theoretically interpreted by Tamm and Frank (1937). We will emphasize that this radiation has nothing in common with the actually always existing bremsstrahlung radiation (in the case of fast electron motion). The latter is emitted by a moving electron when it collides with atoms. However, in the Cherenkov phenomenon, we are essentially dealing with radiation emitted by the medium under the effect of the field of a particle that moves in this medium. The difference between these types of radiation reveals itself most clearly with transition to the limit of any large mass of the particle: the bremsstrahlung radiation vanishes completely, but the Cherenkov radiation does not vary at all."

Noting the convincing explanation of the difference between the two mechanisms (bremsstrahlung and VCR) and the clear indication of the medium as a source of radiation, one cannot but observe that the authors of [18] have not noticed the "nothing in common" between the interaction of the moving electron with the atom and the interaction of the electron with the medium, which also consists of atoms that are spaced at still larger distances from the electron trajectory, whereas Fermi and, later, A. Bohr specifically emphasized the essential generality of these mechanisms.

It seems that there are enough cases that show that the problem has become ripe. Its solution is a sufficiently obvious one. It is worth only to ask a question, "do any grounds exist for discarding the laws of conservation of energy and momentum and Newton's First Law?" The developers of the transition radiation theory do not present any arguments at all, and the authors of the VCR theory refer to the "superluminal character" of this phenomenon. The developers of this theory do not explain what exactly allows discarding the basic laws when the particle moves with a velocity that exceeds the phase velocity of electromagnetic oscillations in the medium but never exceeds the speed of light in vacuum. We will note that the question regards particle velocities that are reached in accelerators within the framework of the laws of electrodynamics and that when accelerated particles hit a solid the same laws continue to act. Thus, one can state that the above conducted detailed consideration proves convincingly that there are no grounds to discard the laws of conservation of energy and momentum, and Newton's First Law. A number of arguments against the VCR mechanism proposed by Tamm and Frank could be listed.

(1) The contradiction of the laws of conservation of energy and momentum.

(2) The contradiction of Newton's First Law.

(3) The absence of any mechanism of radiation when the frame of reference connected with the particle is introduced.

(4) The existence of two mechanisms of moving particle interaction with the same atoms.

The erroneous explanation of the VCR mechanism has become so widespread that, today, in all monographs, reviews, reference books, encyclopedias, and textbooks, only the explanation of the VCR and the transition radiation mechanism is presented that is contradictory to the basic laws, which leads to the destruction of the "cornerstone of the whole of natural science."

A clear and detailed description of the mechanism of the Vavilov–Cherenkov effect that is not a trivial one, although it bears a stopping character, will be given below. The explanation of the VCR mechanism proposed in the present work results from a rather rigorous analysis (without corrections for ranks and titles) of the existing explanations of this mechanism and directly points at the contradictions to the basic laws.

In order to retrace what twists were performed in the process of understanding the VCR mechanism and understand how and why various incorrect explanations arose, it is necessary to turn to the background of the development of the theory of the Vavilov–Cerenkov effect.

2. THE DEVELOPMENT OF CONCEPTIONS OF THE MECHANISM OF VAVILOV–CHERENKOV RADIATION

The explanation of the VCR mechanism brilliantly displays that the way to the truth is hard and tortuous. The historical review should probably begin from O. Heaviside, who as early as 1888 [19] pointed at the possibility of radiation of a charge that moves in a medium with a velocity exceeding the speed of propagation of electromagnetic oscillations. He gave up consideration of the charge motion process with velocity exceeding the speed of light propagation in the ether, but examined a charge motion with the velocity u exceeding the speed of wave v in the dielectric and obtained the following expression for the angle φ formed by the front of the plane wave of radiation relative to the charge trajectory:

$$\sin\varphi = v/u.$$

Subsequently, Heaviside's works on the radiation of the charge moving in the medium were forgotten, being discovered by several readers simultaneously only after almost 90 years had, passed in 1974 [20, 21, 22].

It is also known that Lord Kelvin [23] indicated in 1901 that an atom that moves in vacuum with the speed that exceeds the speed of light must radiate electromagnetic waves. Later, in 1904 A. Sommerfeld [24] also considered the question of radiation of electron motion in vacuum at superluminal speed.

It is worth noting that, in all of these considerations carried out by great scientists, such issues as the mechanism of the radiation generation, the laws of conservation of energy and momentum, and the essential spectral restrictions are not discussed, i.e., the very simplest outline of the process is considered. The charge moves uniformly and rectilinearly and radiates at any frequencies up to infinity, because a medium without dispersion is considered. However, debates on the dispersion absence in the hypothetical medium were limited by wavelengths approaching the size of the moving charge. Of course, there is nothing in vacuum for a charge to interact with. Usually in such problems, the case in which the particle velocity exceeds the speed of light was taken as the cause of the radiation: in the authors' opinions, radiation is to be observed if the particle speed exceeds the speed of light and radiation is absent when the charge velocity is below the speed of light.

Experimentally, such an effect was observed by Cherenkov [25] who. under the guidance of Vavilov. studied the luminescence of solutions under γ-radiation and discovered a new phenomenon. There is no necessity to describe the Cherenkov experiments here; it is only worth noting that they convincingly demonstrated that the radiation observed is not a luminescence. Summing up the results of the research conducted Vavilov [26] gave the following explanation of the new radiation mechanism: "we consider the most probable cause of γ-glow to be radiation due to slowing down of Compton electrons." With this phrase, Vavilov emphasized that the radiation was caused not by γ-quanta as it was considered before, but by electrons that emit the visible radiation resulting from the decrease of their velocity in the medium. Thus, Vavilov described the VCR mechanism as a classically slowing down one.

As was noted by Frank [27], many characteristics of the radiation, such as the instantaneous nature of the excited state and universality and polarization of the glow,, were successfully explained in the framework of this concept. However, attempts to explain the dependence of the radiation intensity on the atomic number of the substance, the radiation directivity, and the absolute radiation yield, which far exceeded the predictions of bremsstrahlung theory, were not a success.

In 1937 Tamm and Frank [1] considered the radiation of a charge moving rectilinearly with uniform velocity along an infinite trajectory in a medium where the phase speed of light is smaller than the charge velocity. Looking at such a formulation of the problem, "higher school graduates" discover that, with any small energy loss for the radiation, the charge velocity will decrease down to the threshold one at some point of the infinite trajectory.

The "young scientists" immediately will object that movement with uniform velocity along an infinite rectilinear trajectory should not be understood literally, but is purely a model approximation that permits neglecting all the processes caused by close collisions of a moving charge with medium charges and consideration of only distant ones; even the radiation losses in these processes can be neglected within the framework of the model chosen.

Still, the developers of the VCR theory decidedly reject such an explanation. In fundamental work [1], they write, "these peculiarities of the phenomenon were considered in detail by Vavilov, who proposed that the glow is caused by the deceleration of fast electrons.

In further experiments Cherenkov revealed the sharp asymmetry of the intensity distribution of this glow, which perhaps is its most characteristic property. It turned out that radiation of light in the direction of the electron motion is much more intense than it is in the opposite direction.

Hence, it immediately follows that matter under electron bombardment radiates coherently at least at a distance comparable in size with the wavelength of visible light. Thus, this radiation can be caused neither by electron scattering on atomic nuclei, nor by interaction with separate atoms.

However, this phenomenon can be explained both qualitatively and quantitatively if it is taken into account that an electron that moves in a medium emits light even when the motion is uniform in the sole case when its velocity exceeds the speed of light in this medium.

It is clear that the question here is not about some approximation in the framework of the model, but concerns the discovery of a new mechanism of radiation generation that was unknown to anybody before. A macroscopic mechanism that assumed radiation of a charge that moves with constant velocity enabled an explanation of all experimental results of the VCR studies. However, a purely model reason ensuring constructive interference was elevated to a principle and gave birth to the annoying misunderstanding that led to the direct counterpositioning of the stopping mechanism to the VCR generation mechanism.

A very interesting evaluation of the above-cited two phrases can be found in the later work [28] of Frank: "the statement in the first phrase must really be well grounded, and the second assertion, if considered as a consequence of the radiation directivity, is simply erroneous. It became evident almost at once, and for a long time it bothered me. However, this phrase has no vital importance for the theory of the Vavilov–Cherenkov effect, and thus there were no grounds for the correction. It is likely that nobody noticed this phrase in all those years for this very reason, although our article was republished in 1967."

Of course, the VCR cannot be caused by scattering on atomic nuclei, but if we admit the interaction with atoms (recalling Newton's First Law at that), then we are forced to admit that the VCR mechanism is a stopping one, and that is the key aspect in VCR theory. It should be noted that, in the above-cited quotation from [1], the authors, on the one hand, stated that "matter under electron bombardment radiates" and, on the other hand, asserted that "an electron that moves in a medium emits light." If, for the case of the electron emitting light, they presented their explanation, still such questions as why the medium radiates and how these processes correlate were left without an answer.

In his memoirs [29], Frank described in detail the attempts to construct the VCR theory: "Tamm presented the qualitative pattern, which allows interpretation of the radiation, to L.I. Mandelshtam. Mandelshtam's remark was that it is known that a uniformly and rectilinearly moving electron does not emit."

Furthermore, he writes, "in the Williams method, the time dependence of the incident particle electric field at some point characterized by an impact parameter was considered. The field dependence on time was represented in the form of the expansion into continuous spectrum of frequencies, and then the action on the atom or nucleus at this point by each frequency ω was determined. As applied to the phenomenon considered the question was how the field carried by the particle becomes a source of waves propagating from each point of the trajectory. Following Williams, it was required to find a small interaction of the particle field with atoms and nuclei along its path the oscillations of which were the source of waves. From the very beginning, I attempted to find a mechanism of transformation of the particle field into diverging waves in order to ground a qualitative pattern. In modern terms, it was an attempt to construct a microscopic theory of the Vavilov–Cherenkov radiation that was not needed. It was typical for that time."

As is seen, all the participants of the discussions in that era, in particular Mandelshtam, stated that, with uniform and rectilinear motion, an electron does not radiate, but nobody pointed out that the very definitions of uniform and rectilinear motion given by Newton's First Law do not allow the possibility of radiation as well.

The "small interaction of the particle field with atoms" in the latter quotation is mentioned quite correctly, but even in 1984 Frank did not consider this mechanism to be necessary. His list of reasons was probably similar to that formulated by Landau and Lifshitz [18] (see the quotation on p. 456). The intensity of bremsstrahlung radiation rises if the particle acceleration increases in absolute value, but the calculation shows that the VCR intensity, on the contrary, decreases with variation of electron velocity. Thus, radiation arises under conditions of uniform and rectilinear motion.

Indeed, the requirement of sufficient constancy of speed within a path length that considerably exceeds the wavelength of radiation is the condition of the macroscopic mechanism that ensures radiation coherence. As far as the microscopic mechanism of radiation is concerned, Frank plainly formulated the problem of its construction, as may be seen from the above-cited quotation, but, unfortunately, the problem would remain unsolved because he considered it unnecessary.

The next stage in the development of the ideas of the VCR features followed after experiments in shaped electron beams with energy from 250 keV to 2 MeV carried out by G.B. Collins and V.G. Reiling in 1938 [30]. The experiments taking into account electron scattering confirmed in general the VCR characteristic directivity that follows from the Tamm–Frank theory, but have not led to a deeper understanding of the radiation mechanism. This points at the difficulty of understanding the mechanism of the VCR generation, even after the theoretical consideration of this problem in [1]. In explaining the VCR mechanism, Collins and Reiling wrote that, "it is to be understood that the electron in its passage through the medium gradually loses nearly all its energy through ionization and excitation processes, and that the resulting acceleration is responsible for the Cerenkov radiation."[4]

Collins and Reiling were acquainted with [1], but, as can seen from the quotation cited, they explained the VCR mechanism without going deeply into the essence of the Tamm–Frank theory. The decrease of the particle velocity caused by the ionization and excitation processes, as was already noted, not only is not the source of VCR, but on the contrary suppresses the latter. Subsequently, Tamm and Frank highly valued their experimental results, but Tamm [31] emphasized that "Collins and Reiling interpreted the physical basis of this theory completely incorrectly ." This may be why the developers of VCR theory associated any reference to the stopping mechanism (including by Fermi and A. Bohr) with an interpretation similar to those proposed by Collins and Reiling and still earlier by Vavilov.

Fermi's work [16] represented a very important stage in the development of ideas on the VCR mechanism, although it was dedicated to the analysis of energy loss of particles that move in a medium. From the quotation presented in the Introduction to this article,we see that Fermi's remark is absolutely correct in essence, but still too general. Objecting to Tamm and Frank, Fermi emphasized that the VCR mechanism corresponds to the Bohr theory, i.e., that the radiation arises from the interaction between a moving charge and the medium's charges, not as the result of the charge's uniform and rectilinear motion.

However, in order to calculate the total loss of energy of a particle moving in a medium, Fermi divided the whole region of particle interaction with the medium into two parts (close- and long-range interactions). As is now clear, Fermi did this because of a deep understanding of both the unity and difference between the mechanisms of moving particle interaction with close and distant charges. His remark on the identity, in principle, of these microscopic mechanisms has to date been given little attention. However, neither Fermi, nor A. Bohr, nor anybody else gave a reasonably clear description of a VCR microscopic mechanism that could solve the misunderstanding.

For Fermi and A. Bohr, this conditional division into close- and long-range interactions represented the confirmation of the identity of electromagnetic interaction of the moving charge both with close charged particles and distant bound electrons. Other readers, nevertheless, interpreted such a division as proof of the essential difference between the mechanisms of close-r and long-range interaction of a moving charge with the medium atoms. The difference between these mechanisms is, of course, important, but for it to be explained there is no need to violate the basic laws.

However, no one but O. Bohr paid attention to these subtleties. We see that, as a result, the stopping mechanism was rejected by an overwhelming majority of votes, publications appearing over the last few decades having disseminated a false mechanism of the radiation of a uniformly and rectilinearly moving charge that contradicts the basic laws, which is now absolutely clear.

To justify Collins and Reiling, it could be said that they did not find a noncontradictory and adequately detailed enough description of the VCR mechanism. Hints as to the real microscopic mechanism appeared a year after the work of Collins and Reiling was published. In [31], Tamm wrote about the microscopic mechanism that "from the standpoint of the microscopic theory, the radiation considered is not emitted directly by an electron, but is caused by coherent oscillations of the medium molecules that are being excited by an electron. However, here we do not enter into the microscopic consideration of the problem." Later, other authors also came to understand that the atoms of the medium radiate, but this did not force them to doubt the reality of the mechanism of charge radiation that moves uniformly and rectilinearly in the medium.

For example, J.V. Jelley, in the beginning of his article [32], writes, "if a fast charged particle moves in a dielectric medium with a constant speed, then the electromagnetic pulse connected to it temporarily polarizes the medium close to the particle trajectory. In this process, individual atoms follow the electromagnetic pulsation of the particle and, thus, themselves become radiators of electromagnetic wave. In the general case, the waves emitted by them and going from all the parts of the trajectory undergo interference, so that at a point some distance from the trajectory the intensity of the resulting field equals zero. However, as often happens, if the particle velocity exceeds the phase speed of light in this medium, then elementary waves outgoing from all the parts of trajec-

[4] The author of the manuscript cites the quotation in the original.

tory may be in phase in some point and produce a resultant field in it."

The author here seems to have tried to give an account of the explanation of the Vavilov–Cherenkov effect that was proposed by A. Bohr, but imported his own interpretation of the underthreshold mechanism, which is erroneous in principle. As will be shown below, in the underthreshold region, radiation is not observed, because the microscopic VCR mechanism displays such a specific feature, but not as a result of destructive interference.

Jelley clearly indicates that a particle that moves in a medium with constant velocity temporarily transfers part of its energy to the medium. There is no preferential direction for the energy to dissipate. From his description, it is absolutely clear that the process of energy transfer from a moving particle to a homogeneous medium proceeds continuously and strictly symmetrically relative to the velocity vector of the particle. In Jelley's opinion as stated in this part of article [32], the electromagnetic wave radiator is not the moving particle, but the atoms of the medium that receive energy from the particle in the process of medium polarization.

In one of the subsequent sections of the same part, Jelley considers the quantum interpretation of the VCR proposed by Ginzburg [11]. Moreover, Jelley's aforementioned reasons that the medium emits the VCR photon, but not the particle, have no effect on his account of the VCR quantum theory. He explains the VCR mechanism so plainly and clearly that no doubts that the moving particle radiates remain. He explains it thusly: "let u be the velocity of the particle (with rest mass m) in the medium before the photon emission. We will assume that, in some section of its path, a photon $h\nu$ is emitted at angle θ relative to the initial direction of the particle and that this leads to instantaneous loss of part of the energy, so that afterward the particle moves with velocity $\mathbf{v}$ at angle φ relative to the initial direction."

If Jelley wrote above that the particle "temporarily polarizes the medium close to the trajectory," then now it appears that the particle emits a photon instantly. The author himself was not confused by this contradiction at all. However, A.A. Tyapkin [33] made quite a definite choice between these two approaches to the VCR mechanism explanation.

Tyapkin resolutely supports the opinion that, in the Vavilov–Cherenkov effect, it is the atoms of the medium that radiate, not the particle. He sharply criticizes Ginzburg for his VCR quantum theory: "Ginzburg took liberties to propose the first quantum theory of the Cherenkov radiation in 1940 [23]. In his work, he neglected Tamm's stipulation that the Cherenkov "radiation" is not emitted directly by an electron, but it comes from coherent oscillations of the medium molecules excited by an electron" [10. p. 79]; he simply assumed that the Cherenkov photon is emitted directly by the primary electron, and, of course, he obtained deliberately false quantum corrections the awkwardness of which has yet to be made a subject of attention. The most surprising that Tamm, in his later works, still continued to refer to this article [23], taking no notice that it absolutely contradicts his correct statement of the secondary nature of the origin of Cherenkov radiation photons."

Tyapkin's remark is correct in its essence, but he had not come to the consideration of the quite alternative explanation of the VCR mechanism (radiation at the uniform and rectilinear motion of the electron), which was also insisted upon by Ginzburg. For the sake of correctness, it should be noted that Tamm has also presented another explanation of the VCR mechanism as, for instance, he did in his Nobel lecture [6], which is cited at the very beginning of this article. It was clearly said there that VCR is emitted by a uniformly and rectilinearly moving particle, but not by the atoms of the medium.

Ginzburg's answer to the Tyapkin's remark was also rather forceful [34]: "Tyapkin considered it unnecessary to show why the corrections obtained in [11] were "deliberately false"." However, he showed nothing but lack of understanding that, in [11], as well as in the work cited by him [20], the macroscopic, not the microscopic, electrodynamics in the medium is quantized."

However, in the same article [34], in reply to a similar remark by other authors, Ginzburg expressed a quite reasonable concern: "In article [19] published in this issue of *Uspekhi Fizicheskikh Nauk* and in some other publications, the question was discussed of whether VC is a 'proper radiation' of a fast particle or medium radiation excited by this particle. The authors of [19] consider VC radiation to be the proper radiation of the particle. Of course, for VC radiation to arise, both a particle (source of energy) and medium are required. Thus, the question of which is more important is somewhat scholastic. However, I still consider VC radiation to be medium radiation, as it is more physically grounded, although this is not inescapable. This is especially reasonable taking into account that the VC effect takes place even without any source—that is, particle—for instance, if the source is a pulse of light (see above). The same standpoint is adopted in [15, §115]."

To my mind, the last question is not scholastic, because if, nevertheless, nonuniformly moving charges in atoms radiate, then it appears that the "dogma" is also acting in the VCR mechanism. The role of the moving particle in the radiation process turns out to be absolutely analogous to that it plays, for example, when it ionizes, not polarizes, an atom. In such a case, no one insists that the ionizing particle emits the characteristic radiation, though the energy of this radiation comes from the particle. Of course, doubt is left as to how the particle that is the source of energy for the emitting medium can still move in this medium uniformly, which was emphasized by Ginzburg even in the title of publication [34].

Thus, the consideration of different standpoints on the mechanism of the VCR generation demands unusual self-control and absolute objectivity when evaluating the proposals of eminent scientists, including Nobel Prize winners.

Tyapkin also failed to avoid drawing an important, but incorrect in principle, conclusion that directly applies to the interpretation of the VCR microscopic mechanism. In [33] he writes, "indeed, if a dipole polarized by an electromagnetic wave emits light, then dipoles created by a charged particle at the moment of its passage also can be sources of coherent radiations that, under certain conditions, will unite and form directed Cherenkov radiation. *However, these conditions of radiation threshold have nothing to do with the very initial radiation, which results from the medium atoms' polarization under the action of the electric field of the passing charged particle. Thus, the requirement of the threshold for the initial radiation, which is the basis of Cherenkov radiation, is a very gross error*."

Unfortunately, one is forced to acknowledge that the conclusion I have called attention to, which was formulated by Tyapkin in a categorical form, is nevertheless incorrect in principle. A similar explanation of the underthreshold mechanism was also proposed by Jelley, as can be seen from the quotation cited on p. 459. Explanations of this sort can also be found in publications of other authors. This question, which is essential to the Vavilov–Cherenkov effect, will be completely clarified in the consideration of the real VCR microscopic mechanism.

The next example demonstrates how closely some authors have approached understanding the incorrectness of modern explanation of the VCR mechanism. This example is taken from the work of still another eminent scientist, D.V. Skobeltsin [35]. He writes, "taking into account these questions, it is possible first to recollect the following well-known proposition: a free electron that moves rectilinearly and uniformly in vacuum cannot radiate light at the expense of its kinetic energy. Based on the fundamentals of relativity theory, one could come to such a conclusion immediately after introducing the inertial frame of reference, in which the electron is considered at rest, and, hence, the energy needed for the photon to be emitted under the given conditions equals zero. However, as is well known, an electron in a state of uniform motion in a medium produces such radiation—that, is Vavilov–Cherenkov radiation."

As we see, Skobeltsin irrefutably proved that the rectilinearly and uniformly moving electron can never radiate because the frame of reference connected with the moving electron is an inertial one. This was presented as a "well-known proposition," but that an electron radiating in a medium moves uniformly, in his opinion, also does not require proof, as it is "well known" as well.

All the contradictions and "awkwardness" that were marked by Tyapkin with all the straightforwardness peculiar to him surround the Vavilov–Cherenkov effect with a mysterious atmosphere supplemented with hints of the "superluminal character" of this phenomenon. The "higher school graduates" and "young scientists" try to follow the thoughts of the great scientists, but more often than not they stumble on statements that contradict one another and even themselves, and also are contrary to the basic laws.

From the short historical review of the development of ideas about the VCR mechanism conducted in this chapter, one can see that the prominent scientists mistakes in its explanation were caused, first of all, by the complicated character of this phenomenon, which they usually tried to explain in the simplest manner. The very delicate question of the relationship between the VCR and the bremsstrahlung in the majority of cases was solved in the simplest way. Arguments from one side were concentrated on the difference of this phenomenon from the bremsstrahlung. They rejected this mechanism so resolutely that they failed to see any similarity to it right up to the violation of the basic laws. The opposite side considered the demands of the laws of conservation of energy and momentum to be so evident that there was no need to explain anything, also paying to attention to the difference from the bremsstrahlung radiation.

A detailed and accurate discussion of mistakes made by different authors while creating the Vavilov–Cherenkov effect theory is absolutely necessary for finding the correct explanation of this phenomenon. The information accumulated through the course of more than 70 years gives an opportunity now to propose an exhaustive explanation of the VCR mechanism that does not require any deviations from the basic laws of mechanics. Quite the contrary, strictly following these laws gives hope that the explanation proposed below of the VCR mechanism is correct and describes all the features of this interesting phenomenon.

3. THE THEORY OF THE VAVILOV–CHERENKOV EFFECT

Before we go on to the consideration of the Vavilov–Cherenkov effect mechanism, it is necessary to formulate the general conditions. The problem of charged particle motion along a rectilinear trajectory in a homogeneous transparent medium will be solved in the framework of classical electrodynamics. This means that we exclude from consideration close-range collisions of the incident particle with medium atoms that lead to ionization of atoms or to its scattering in a nuclei field, i.e., those wherein the medium ceases to be homogeneous and the incident particle interacts with a separate atom or nucleus.

The question of excluding close-range interactions from consideration is not as simple as when we neglect some minor effect in comparison with a major and dominant one. Quite the opposite—here, we do not consider the stronger fields close to the particle trajectory that lead to medium ionization, the knocking out of recoil nuclei, and deflection of the very incident particle, i.e., to the variation of our model. The model indicated above is completely inapplicable for description of interactions when the incident particle deflects from the rectilinear trajectory in the field of the nucleus.

On the other hand, here we do not state that the particle moves within some channel with no medium inside, and so exclude close-range interactions. If such a supposition is made then it'll be a case of the moving particle field propagation in the inhomogeneous medium. Thus when we talk about the exclusion of close-range interactions from consideration we rather mean some model technique that limits the spectrum of frequencies considered.

We will be interested in the interaction of the charged particle with atoms and molecules of the medium, which reside at such a long distance from its trajectory where the maximum intensity of the field created by it turns out to be insufficient for atom ionization, but leads to its polarization only. It is the interaction of a charged particle with a system of bound charges distinguishes the Vavilov–Cherenkov effect from the bremsstrahlung, which is often confused with it (Collins and Reiling, Vavilov).

This system of bound charges (quasi-elastic dipoles) is directly present in the theoretical considerations of the VCR mechanism, as we describe electromagnetic oscillations of low enough frequency in the homogeneous transparent medium with dielectric constant ε, which explicitly depends on the number of electrons in the volume unit N in the form of

$$\varepsilon = 1 + \frac{4\pi N e^2}{m\nu_0^2}, \tag{1}$$

where ν_0 is the frequency of atom oscillators, e is the charge of the electron, and m is the electron mass.

Equation (1) is present in many publications dedicated to the Vavilov–Cherenkov effect, but most authors incorrectly explain the character of the moving charge interaction with the system of bound charges—in particular, in the underthreshold region.

The theoretical consideration of the Vavilov–Cherenkov effect in this article will generally follow fundamental work [1]. In [1], as in many subsequent publications, the problem of the charge motion in a homogeneous, transparent, and nonmagnetic medium is solved in the framework of the classical laws of electrodynamics. The process of medium polarization in the field of the moving charge takes place in accordance with the equation that determines the relation between polarization $\mathbf{P}$ and intensity of the electric field $\mathbf{E}$:

$$\frac{\partial^2 \mathbf{P}}{\partial t^2} + \sum_s \omega_s^2 \mathbf{P}_s = \alpha \mathbf{E}, \tag{2}$$

where ω_s is the frequency of atom oscillators without external field and α is the volume polarizability of medium.

The values that characterize the field can be represented in the form of the Fourier integral:

$$\mathbf{E} = \int_{-\infty}^{\infty} \mathbf{E}_\omega e^{i\omega t} d\omega, \quad \mathbf{P} = \int_{-\infty}^{\infty} \mathbf{P}_\omega e^{i\omega t} d\omega,$$

while the Fourier-components of these values are connected by the relation

$$\mathbf{P}_\omega = (n^2 - 1)\mathbf{E}_\omega,$$

where n is the refractive index for frequency ω.

The problem of the moving charge interaction with the medium is being solved using the Maxwell equations:

$$rot\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}, \tag{3}$$

$$rot\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} + \frac{4\pi}{c}\mathbf{j}, \tag{4}$$

$$div\mathbf{H} = 0, \tag{5}$$

$$div\mathbf{D} = 4\pi Q, \tag{6}$$

$$\mathbf{D} = n^2\mathbf{E},$$

where $\mathbf{j}$ and Q are the current density and charge density created by the incoming particle.

Using the well-known relations

$$\mathbf{E} = -grad\varphi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}, \tag{7}$$

$$\mathbf{H} = rot\mathbf{A}, \tag{8}$$

and also the additional condition of Lorentz gauge,[5]

$$\frac{n^2}{c}\frac{\partial \varphi}{\partial t} + div\mathbf{A} = 0, \tag{9}$$

we will go on to the equations for the vector $\mathbf{A}$ and the scalar φ potentials:

$$\nabla^2\mathbf{A} - \frac{n^2}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = -\frac{4\pi}{c}\mathbf{j}, \tag{10}$$

$$n^2\left(\nabla^2\varphi - \frac{\varepsilon}{c^2}\frac{\partial^2 \varphi}{\partial t^2}\right) = -4\pi Q. \tag{11}$$

The solution of the problem reduces to the solution of only one equation (10).

If the current density and the charge density do not depend on time, then the corresponding derivatives in

[5] The Lorentz gauge (introducing, in particular the frame of reference that is connected with the moving charge) excludes the possibility of radiation at uniform and rectilinear motion of the charge.

Eq. (10) turn out to equal zero and naturally no radiation is expected. If only one charged particle still moves in the medium with the charge q, then the current density created by it is usually represented in the form of the Dirac delta function:

$$\mathbf{j} = q\mathbf{v}\delta(x)\delta(y)\delta(z-\mathbf{v}t). \tag{12}$$

In Eq. (12) the particle velocity $\mathbf{v}$ is assumed to be constant, i.e., we do not take into account energy losses of the moving particle for radiation, which conforms to the violation of the law of conservation of energy.

In order to emphasize the lack of logic in the supposition of some "superluminal" mechanism, we will consider the charge motion with the constant velocity $\mathbf{v}$ in the medium with dispersion for the two Fourier components ω_1 and ω_2. The charge velocity will be chosen for the following conditions to be met on these frequencies:

$$\beta n_1 > 1 \text{ at the frequency } \omega_1, \tag{13}$$

$$\beta n_2 < 1 \text{ at the frequency } \omega_2, \tag{14}$$

where $\beta = v/c$.

For this, we expand the current density $\mathbf{j}$ in a Fourier series. Then the Fourier component of the current density will be written in the form

$$j(\omega) = \frac{q}{2\pi}e^{\frac{i\omega z}{v}}\delta(x)\delta(y). \tag{15}$$

We rewrite Eq. (10) for the Fourier components:

$$\nabla^2\mathbf{A}(\omega) - \frac{\varepsilon(\omega)}{c^2}\omega^2\mathbf{A}(\omega) = -\frac{4\pi}{c}\mathbf{j}(\omega). \tag{16}$$

As the problem is an axially symmetric one, then, going on to the cylindrical frame of reference (ρ, φ, z), we obtain

$$\mathbf{A}_\rho = \mathbf{A}_\varphi = 0.$$

The solution of Eq. (16) should be searched for in the form

$$A_z(\omega) = a(\rho,\omega)e^{-\frac{i\omega z}{v}}. \tag{17}$$

In this case, the function $\alpha(\rho, \omega)$ will satisfy the Bessel equation of zeroth order for all ρ values, but, when $\rho = 0$,

$$\frac{\partial^2 a(\rho,\omega)}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial a(\rho,\omega)}{\partial\rho} + s^2 a(\rho,\omega) = -\frac{q}{\pi c\rho}\delta(\rho), \tag{18}$$

where $s^2 = \frac{\omega^2}{v^2}(\beta^2 n^2 - 1) = -\sigma^2$.

Introducing the new variable $s\rho$, we write the Bessel equation in the following form:

$$\frac{\partial^2 a(s\rho,\omega)}{\partial(s\rho)^2} + \frac{1}{s\rho}\frac{\partial a(s\rho,\omega)}{\partial(s\rho)} + a(s\rho,\omega) = 0. \tag{19}$$

Without going into the details of the solution of Eq. (19), we will write out the final expression for the vector potential at the frequency ω_1, which was obtained in [1] under condition (13):

$$A_z(\omega_1) = -\frac{q}{c\sqrt{2\pi s\rho}}e^{i\omega_1\left(t - \frac{z\cos\theta + \rho\sin\theta}{w}\right) + \frac{3}{4}\pi i}, \tag{20}$$

where $\theta = arc\cos(1/\beta n)$ and $w = c/n$.

The sharply directed radiation at the angle θ appears as a result of constructive interference of waves at the frequency ω_1 that emerge along the rectilinear trajectory of the particle (macroscopic mechanism).

Consequently, the authors of [1] find the components of the electromagnetic field in the wave zone and calculate the value of energy radiated through the surface of the cylinder with the length l. Assuming that the particle velocity is constant, they obtained the following expression for the energy of radiation at all frequencies that comply with condition (13):

$$W = \frac{q^2 l}{c^2}\int_{(\beta n > 1)} \omega d\omega\left(1 - \frac{1}{\beta^2 n^2}\right). \tag{21}$$

The solution of Bessel equation (19) at the frequency ω_2 for a charge moving with the same velocity is also of interest. In [1] under the condition of $\beta n_2 < 1$, the following expression for the vector potential was obtained:

$$A_z(\omega_2) = \frac{q}{ce^{s\rho}\sqrt{2\pi s\rho}}e^{i\omega_2\left(t - \frac{z}{v}\right)}. \tag{22}$$

Wave (22) contains an amplitude that rapidly decays as ρ increases, which illustrates that there is no radiation at the frequency ω_2.

Thus, the calculation demonstrated that a charge moving in a medium with constant velocity along an infinite trajectory radiates a conical wave at one frequency ω_1 and does not radiate at the frequency ω_2.

Why does a charge that moves in a medium radiate at certain frequencies and not radiate at others? It is most likely that the answer to this question should be looked for in the structure of this medium, not in a "superluminal" velocity of the charge, which for other frequencies appears to be "subluminal."

The calculation presented above in the framework of classical electrodynamics cannot give an idea of the microscopic mechanism of the Vavilov–Cherenkov effect, as in this calculation the medium is considered to be absolutely homogeneous and its atomic structure is not displayed in any way. The macroscopic mechanism of the interaction of a particle that moves along an infinite trajectory still leads to such peculiarities as the threshold and radiation at the fixed angle.

Numerous publications on the theme of the Vavilov–Cherenkov effect have contained similar calculations that demonstrated the obscure mechanism of radiation of a particle that moves in a medium uniformly and rectilinearly. In addition, although some authors [17, 18, 31, 32, 33, 34] asserted that radiation is not emitted by the particle, but by polarized atoms, still this fact had no substantial influence on the expla-

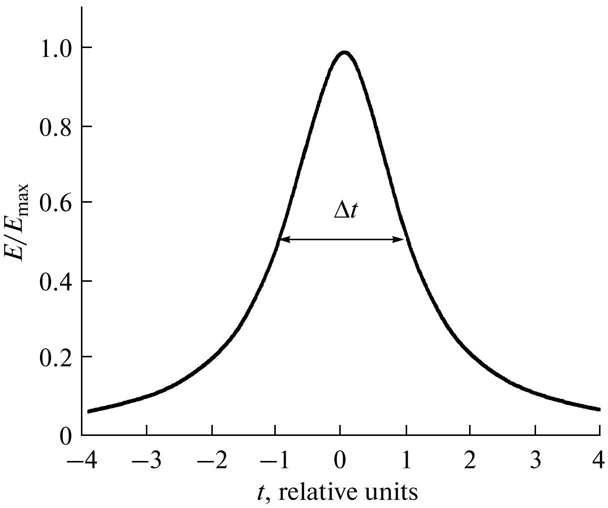

Fig. 1. The character of the variation of the modulus of electric field intensity at the point ***M*** when the speed of the incoming charged particle is below the phase speed of light in the medium.

nation of the Vavilov–Cherenkov effect as a specific mechanism of radiation with uniform and rectilinear motion of a charge in a medium.

A clear mechanism of interaction of the moving charged particle with the medium that gives a direct answer to the question of why polarized atoms radiate at a frequency ω_1 and not at a frequency ω_2 will be proposed below.

4. CLEAR EXPLANATION OF THE GENERATION MECHANISM OF VAVILOV–CHERENKOV RADIATION

For a more clear understanding of the mechanism of VCR generation, it is necessary to consider the propagation of a light wave in transparent dielectric. When a light wave propagates in the dielectric, its electric field polarizes atoms of the dielectric and the motion of oscillating charges (quasi-elastic dipoles) produces a secondary wave that interferes with the initial one, hence causing the phase shift. Thus, the action of the medium on a light wave reduces to its phase speed variation. For correct comprehension of the processes taking place, one should not fail to take into account that the variation of the phase speed of light in a medium results from the interference of waves excited by numerous moving charges: each individual wave propagates with speed of light in vacuum. Thus, when considering a light wave that propagates in a medium of a certain refractive index, we thereby take into account the interaction of the wave with the medium charges, i.e., ordinary phenomena take place that are described by the laws of classical electrodynamics. From what has been said above, it becomes clear that the presentation of the Vavilov–Cherenkov effect as a "superluminal" phenomenon appears to be somewhat an exaggerated.

We will begin to explain the VCR mechanism for the case in which atoms and molecules that were polarized by the moving charge do not radiate, i.e., when the charge moves with a low velocity compared with the phase speed of light in a medium.

When a charge moves in a medium at nonrelativistic velocity, the electric field in the point M at some distance r_0 from the charge trajectory is actually a Coulomb one and has the form

$$\mathbf{E} = \frac{e\mathbf{r}}{4\pi\varepsilon r^3}, \qquad (23)$$

where $\mathbf{r}$ is the vector directed to the point M from the current position of the moving charge and ε is the dielectric constant of the medium.

Figure 1 shows the variation of the intensity modulus of the electric field in the point M, which is created by a charge moving in a medium along the axis z with a uniform velocity that is low compared with the phase speed of the wave. For the microscopic VCR mechanism to be understood correctly, it is necessary to emphasize that the point M is situated at a distance from the particle trajectory such that the maximum value of the field created by it does not lead to the atom's ionization, but to its polarization only.

The field increases up to the maximum value, as the charge approaches the point M. Accordingly, the polarization follows the electric field variation in conformity with Eq. (2). Of course, approaching the point M the charged particle spends the part of its energy for the medium polarization. As the medium is a homogeneous one, then the transfer of energy takes place strictly symmetrically relative to the particle's trajectory and does not lead to the deflection of the trajectory from a rectilinear one. During charge motion along an infinite rectilinear trajectory, the direction of the vector of the electric field intensity in the point M smoothly varies to 180° in the plane to which belong both the particle trajectory and the point M.

As in the point M considered here, if the atoms in the process of polarization received energy that has not led them to ionization, then the couplings of electrons with nuclei were not disturbed and the medium returns to the outgoing particle the energy spent for the polarization during its approach. This process takes place in accordance with Newton's Second Law: to every action there is an equal and opposite reaction. As the electric field in the point M varies slowly, then the withdrawing charge removes the polarization completely and restores the initial state of the atoms (molecules).

Such processes take place in all points situated symmetrically relative to the particle trajectory. In this case, radiation does not arise; the particle moves with an almost constant velocity, but even in such a case the motion cannot be considered as a uniform and rectilinear one corresponding to Newton's First Law.

Moreover, a particle that moves in the medium ionizes the closely situated atoms simultaneously and knocks out recoil nuclei, i.e., spends energy considerably. However, we do not include these losses in the framework of the long-range interaction model.

The obvious explanation of the Vavilov–Cerenkov effect for underthreshold velocity of a charged particle given here clearly demonstrates that, in this case, the radiation is not dumped by the interference of waves that arise in the medium along the particle trajectory. The process of particle interaction with the medium bears a nonradiation character in principle.

Comparing this conclusion with the explanations of the microscopic mechanism proposed by Jelly [32], Tyapkin [33], and by many other authors, who stated that atoms polarized by the moving particle radiate at any velocity of the particle and that the radiation below threshold vanishes as a result of destructive interference (macroscopic mechanism), one is forced to recognize the incorrectness of their assertions.

Of course, the conclusion that a particle that moves at underthreshold velocity and interacts with a medium does not excite radiation in it concerns the Vavilov–Cherenkov effect only and does not apply to other processes of interaction of a moving charged particle with the medium. This conclusion also does not extend to the transition radiation, the mechanism of which somewhat differs from the VCR mechanism.

We will also consider the case of charge motion with a velocity exceeding the phase speed of light in a medium. Then the dependence of the field intensity in the point M on $\mathbf{r}$ will have the form

$$\mathbf{E} = \frac{e\mathbf{r}(1-\beta^2)}{4\pi\varepsilon r^3(1-\beta^2\sin^2\varphi)^{3/2}}, \tag{24}$$

where φ is the angle between vector $\mathbf{r}$ and the vector of the particle velocity.

The time dependence of the modulus of the electric field intensity at the point $\boldsymbol{M}$ (full width at half maximum) substantially decreases with β tending to 1. Therefore, the rate of decay of the electric field caused by the outgoing particle turns out to exceed the rate of the field variation of the quasi-elastic dipole (Fig. 2). The interaction of polarized atoms between one another does not allow the wave to follow the quick variation of the electric field of the moving charge. As a result, the freely oscillating quasi-elastic dipoles radiate the energy that they received, in full conformity with the law of conservation of energy.

The nonuniform motion of charges in the polarized atom (molecule) is exactly that of the microscopic stopping mechanism responsible for the Vavilov–Cherenkov radiation. Thus, the proposed explanation of the VCR mechanism allows one to say that, in this phenomenon, as well as in every known before the process of the charge radiation in the electric or magnetic fields, the charges that move with acceleration do radiate. Therefore, the "theorem," the "rule," the

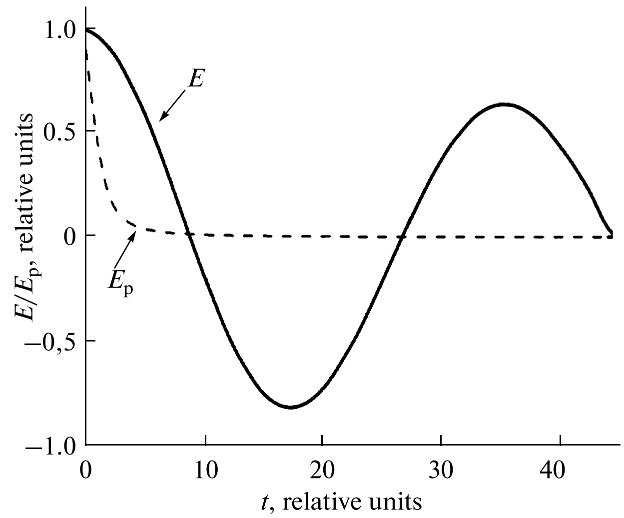

Fig. 2. The time dependence of intensity modulus of the electric field (dashed line) that is created by the particle passing closely by the point $\boldsymbol{M}$ with a speed exceeding the speed of wave propagation in the medium. The solid line shows the electric field intensity of the quasi-elastic dipole.

"proposition," or the "dogma," as prominent scientists call it, represents the direct consequence of the law of conservation of energy and is quite naturally inscribed in the VCR microscopic mechanism.

The necessary condition of such a mechanism is the presence of a large quantity of atoms that slow down the propagation of the electromagnetic wave, the wavelength of which should considerably exceed the interatomic distance. For a separate atom or for several atoms situated in vacuum, such a process is impossible, as their polarization will change with the speed of light in vacuum.

The problem considered is characterized by strict axial symmetry relative to the particle trajectory because the medium is supposed to be homogeneous. Therefore, there are no grounds to expect the smallest deflection of the particle from the rectilinear trajectory. We emphasize that we are not dealing here with neglect of minor deviations, as was noted in quantum theory [11], and the solution of the problem is, in principle, strictly a symmetrical one relative to the charged particle trajectory. However, the moving particle spends its kinetic energy on medium polarization and slows down in full accordance with the law of conservation of energy, i.e., moves nonuniformly. However, this nonuniformity is a consequence of the energy losses for medium polarization and is not a cause of the radiation. Of course, in the framework of some model for the solution of a problem to be simplified, it is possible to assume that a particle moves at constant velocity, which is exactly what was done in [1].

The proposed explanation of the VCR mechanism confirms its stopping character, but its difference from the mechanism of bremsstrahlung radiation, which is emitted by a particle moving in the field of an isolated nucleus, is so much considerable that they should not be identified in any way. On the other hand, the assertion that the mechanisms of bremsstrahlung and VCR have "nothing in common" is an obvious exaggeration. Precisely this exaggeration was noted by Fermi [15] and O. Bohr [16].

The above-given clear explanation of the VCR mechanism gives an idea about how, when, and why polarized atoms of the medium radiate. Such is the microscopic mechanism of the Vavilov–Cherenkov effect. It should be noted that, in the explanation given, there are no propositions that would require violation of the basic laws and there is no need to justify them with the "superluminal" character of the Vavilov–Cherenkov effect.

5. BASIC FEATURES OF VAVILOV–CHERENKOV RADIATION

Resulting from the theoretical consideration of the Vavilov–Cherenkov effect carried out in [1] in the framework of an idealized model (the constant velocity of the particle along the infinite rectilinear trajectory), the main features of the VCR show up very unusual:

(1) The radiation is observed at the angle of $\cos\theta = 1/\beta n$ only.

(2) The radiation vanishes when the particle velocity is below the threshold one $\beta = 1/n$.

(3) The radiation intensity linearly depends on the thickness of the radiator.

(4) The radiation is completely linearly polarized, so that the electric vector of the wave is in the plane that contains the particle trajectory and the observation direction.

(5) The VCR spectrum is determined by the condition $\beta n > 1$.

Many authors of publications on the VCR consider the radiation of a charged particle in a medium that does not have the dispersion. Such a consideration is possible, but only as a model approximation. It is clear that the medium can be considered homogeneous only for radiation with a wavelength far exceeding the interatomic distances. Exactly under such a condition, the calculation of the radiation was carried out in [1]. Otherwise, when a moving particle interacts with separate atoms that are closely situated relative to its trajectory, the model given turns out to be unacceptable.

Seemingly, having in mind this circumstance, the authors of [1] also substituted in the expression for the radiated energy (21) infinite limits of integration over frequency for the condition $\beta n > 1$ and emphasized that the rectilinear path of the electron in the medium l must be far larger than the radiation wavelength:

$$l/\lambda \gg 1. \tag{25}$$

Requirement (25) is rather difficult to meet in real experimental facilities, because l should not be understood as the length of a real radiator, but as the value for which the condition of coherence [4] can be fulfilled:

$$Td(\beta n)/dt \ll 1. \tag{26}$$

Condition (26) imposes the restriction that the variation of βn value during oscillations period T should be far below unity. As a result, in real experiments when the execution of conditions (25) and (26) is not sufficiently strict, the VCR features vary considerably. The total losses of energy along the particle passage in the medium can lead to inadequate fulfillment of conditions (25) and (26). Multiple scattering of the charge along the passage in the medium also leads to deflection of its actual trajectory from rectilinear. Therefore, the radiation observed in the experiment may not have a sharp directivity.

Usually, in the experiments a radiator of finite thickness is situated in vacuum and the registering detector "sees" two boundaries. If the real radiator represents a plane-parallel plate and the charged particle goes through it along the normal to the surface, then if condition (25) is fulfilled, VCR in vacuum will be observed at an angle of

$$\theta_0 = \arcsin\sqrt{n^2 - 1/\beta^2}. \tag{27}$$

In the case in which the radiator thickness does not meet condition (25), the angular distribution of radiation is characterized by some diffractive width [36]:

$$\Delta\theta = \frac{2.78\lambda}{\pi a\beta\sin\theta_0\cos\theta_0}. \tag{28}$$

The real angular distributions of the electron-excited VCR in radiators made of mica were studied in [37]. Figure 3 shows the experimental and calculated angular distributions of VCR excited by electrons with an energy of 210 keV in the radiator with 2.5 μm thickness for several wavelengths ranging from 2500 Å ($l/\lambda = 10$) to 5000 Å ($l/\lambda = 5$). As is seen, the experimental angular distributions fairly well coincide with the calculated ones (solid line) that describe radiation of an electron passing through the plate situated in vacuum [37]. In this calculation, the effect of multiple scattering of electrons in mica is also taken into account. Evidently, with such a thickness of the radiator, the multiple scattering effects appears to be not so important, because the yield of radiation polarized in the transverse plane turned out to be insignificant, both from the calculation and from the experiment. If in calculation by formula (7) from [38] only the diffractive effects (dot-dashed line) are taken into account, then the width of angular distribution noticeably decreases, but still remains substantial, even with $l/\lambda = 10$ and an electron energy far exceeding the threshold value.

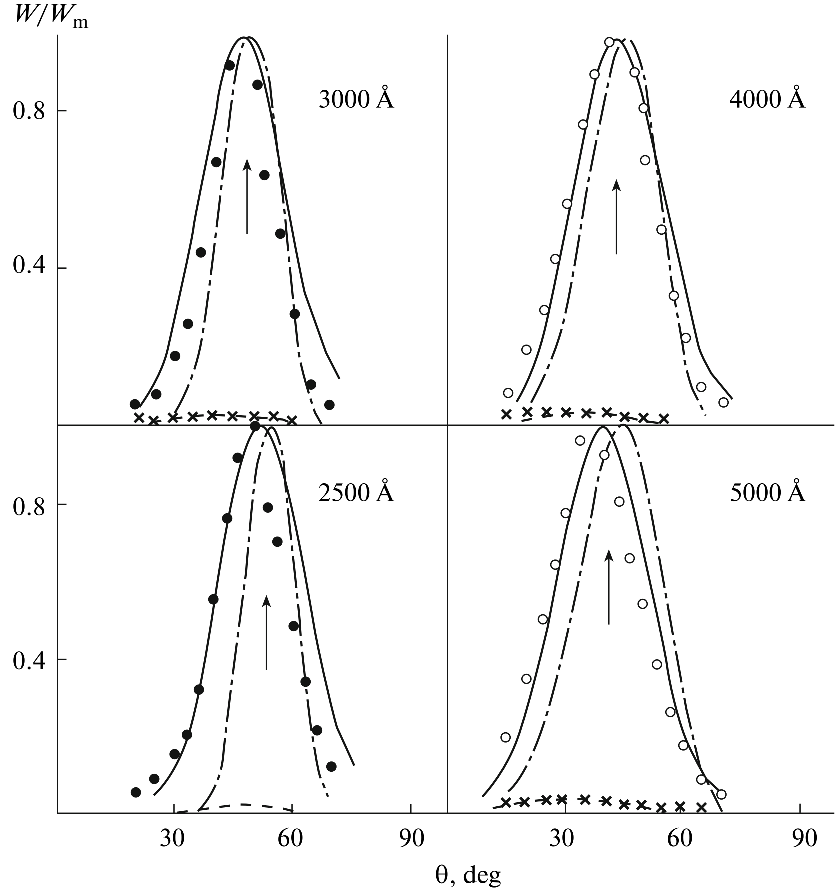

Fig. 3. Angular distributions of the Vavilov–Cherenkov radiation excited by electrons with energy of 210 keV in a mica plate with 2.5 μm thickness. Solid (dashed) lines show the calculation of the longitudinally (transversely) polarized radiation component taking into account multiple scattering of electrons in mica, dot-dashed lines display the calculation by approximate formula (7) from [39], and points (crosses) are experimentally measured radiation yields for longitudinally (transversely) polarized radiation components. Arrows mark angles calculated by formula (27).

Thus, experimental research and proper calculations show that, in most practical cases, VCR is characterized by a more or less wide angular distribution and the feature of the sharp directivity is connected with the limiting model conditions only.

The position of the maximum in the VCR angular distribution for a real radiator located in vacuum also does not follow relation (27) quite precisely. Figure 4 shows that, for a radiator made of mica 12.4 μm thickness at the wavelength $\lambda = 4000$ Å, noticeable deviations from relation (27) are observed; the latter is also obtained for the limiting case under condition (25) and is a characteristic of the VCR stipulated for model reasons.

In Fig. 4 taken from [39], it might also be seen that the energy dependence of the maximum location in the angular distribution does not have any characteristic properties under the condition $\beta = 1/n$; i.e., strictly speaking, the VCR threshold is absent. As follows from calculation in the framework of the idealized model (dotted line in Fig. 4), a radiation threshold should be observed with an electron energy of 149 keV. However, for a real radiator, the main diffractive peak vanishes absolutely for the energy 89 keV only. This is confirmed by both calculated and experimental results shown in Fig. 4. With still lower electron energies, the radiation excited in the mica radiator does not vanish completely, because transition radiation, which is close by nature to VCR, is observed. Moreover, the character of the polarization of radiation remains invariable.

From these experimental and calculation studies, it might be concluded that the VCR threshold is also a result of the limiting model conditions. The absence of the radiation threshold in practical cases is an additional argument that disproves that the threshold is the exact boundary where the "superluminal" mechanism springs up.

It is worth discussing in more detail the spectral features of the VCR, taking into account the peculiarities of the VCR generation mechanisms both of the microscopic character and of the macroscopic one.

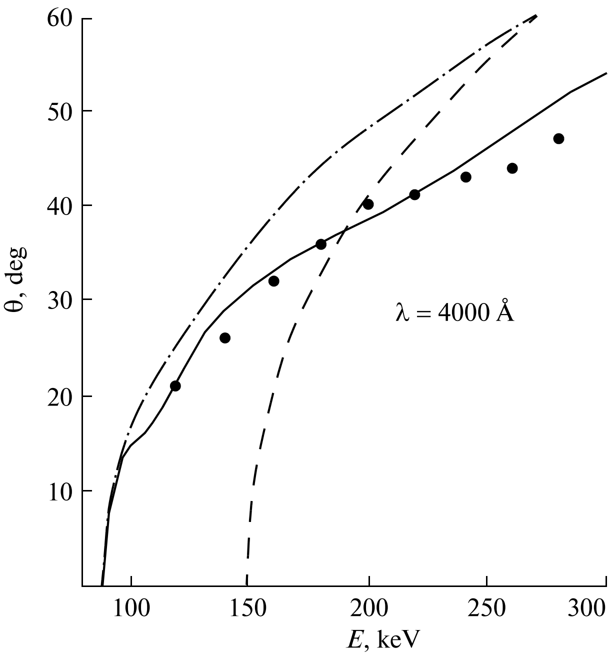

Fig. 4. Energy dependence of location of angular distribution maximum of the VCR excited by electrons in a mica radiator with 12.4 μm thickness. Dashed line shows the calculation by formula (27), dot-dashed line shows the calculation by approximate formula (7) from [38], solid line is the calculation by formulas (17)–(21) from [39], and points display the experimental results.

The microscopic VCR mechanism imposes the following restrictions in principle on its spectrum:

(1) The only bound electric charges in the medium can ensure the required character of the interaction.

(2) The binding energy of electrons in atoms of the medium limits the radiation spectrum from the short-wave side.

(3) The wavelength at the short-wave bound of the VCR spectrum must considerably exceed the interatomic distance.

Many authors discussing the VCR effect emphasize that they neglect close-range interactions of the incident particle with atoms of the medium. Still, when the short-wave spectral bound is considered, the formal usage of the refractive index often leads the authors to regions with such high frequencies that the above-listed conditions for VCR excitation are completely absent.

When considering the possibility of VCR generation in different spectral ranges or any exotic cases of VCR excitation, we must take into account both the requirements of the macroscopic mechanism (uniformity of speed at the long enough section of the trajectory in comparison with the radiation wavelength) and the above-listed requirements of the microscopic mechanism. It is absolutely evident now that the fulfillment of the formal demand for the refractive index ($n > 1$) at some frequency of electromagnetic oscillations in the medium still is not sufficient for the VCR effect to occur at this frequency.

From the understanding of the microscopic mechanism, it directly follows that the Vavilov–Cherenkov effect cannot be observed in the X-ray spectral region or in a region with still higher frequencies [40, 41, 42], because the particle will not transfer the necessary energy to the atom without its ionization. Ionized atoms will of course emit radiation, but this has nothing in common with the Vavilov–Cherenkov effect. Extension of the Vavilov–Cherenkov effect to the γ-ray region comes into conflict with all the restrictions that follow both the microscopic and the macroscopic VCR mechanisms. Several more reasons could be presented that exclude the possibility of the Vavilov–Cherenkov effect onset in X-rays, all the more so in the γ regions of the spectrum:

(1) At the close-range interactions necessary for sufficient energy transfer, the particle interacts with a separate atomic nucleus, but not with the homogeneous medium, which is contradictory to the model used in the VCR theory.

(2) References to the radiation formation length are groundless, because in the Vavilov–Cerenkov effect only the electric field components that are transversal to the particle trajectory are taken into consideration.

(3) An incident relativistic particle in close collisions destroys the atomic structure of the solid through the knocking out of electrons and recoil nuclei. Therefore, the structure of the medium that ensures a certain excess of the refractive index above the unity for the X-ray electromagnetic wave turns out to be destroyed by the incident particle. Thus, the value of the dielectric constant of the homogeneous medium for electromagnetic waves in the X and γ-ray ranges can be spoken about only in the absence of an external field, which leads to the structural changes of the medium.

As for the long-wave boundary of the VCR spectrum, it is basically determined by the condition $\beta n(\omega) > 1$, but the total energy losses of a particle that moves in the medium impose individual spectral restrictions in each particular case.

Such are the main VCR features in practical experimental conditions, the considerable differences of which from those obtained in the framework of the idealized model are stipulated by the peculiarities of the real microscopic mechanism.

6. CONCLUSIONS

The principal conclusions to be drawn resulting from the discussion carried out in the given article concern not only the VCR mechanism, but they bear a considerably general character:

(1) There are no grounds to discard the laws of conservation of energy and momentum when explaining the mechanisms of the radiation by moving charges.

(2) The uniformly and rectilinearly moving particle cannot radiate energy under any conditions according to the laws of conservation of energy and momentum and Newton's First Law.

(3) The suggestion to discard the laws of conservation of energy and momentum of some of the most authoritative scientists represents a grave danger for modern scientific development, as it leads to destruction of something that Max Laue called the "cornerstone of the whole of natural science (see epigraph to this article).

The following conclusions directly deal with the mechanism of VCR generation:

(1) The mechanism of the VCR generation is a stopping one, i.e., radiation arises as the result of polarization interaction of the incident particle with bound charges of the homogeneous medium and the subsequent emission of electromagnetic radiation by these charges.

(2) Atoms of the medium that were polarized by the field of the incident particle emit radiation when the particle velocity exceeds the phase speed of wave propagation in the medium.

(3) Polarized atoms do not emit radiation if the velocity of the particle is smaller than the phase speed of wave propagation in the medium. In this case, atoms have time to return the energy spent for their polarization to the particle.

(4) In theoretical consideration of the Vavilov–Cherenkov effect, model reasons are usually introduced (constant speed of charge, infinite length of trajectory, medium without dispersion), which have an influence on the calculated characteristics of the radiation. Taking into account the real experimental conditions leads to considerable variation of the VCR characteristics.

(5) The condition of coherence demands a rather constant velocity of the charged particle motion, but, practically speaking, this condition is more or less fulfilled only at the limited section of the particle trajectory. This leads to variation of the basic properties of VCR formulated in the framework of the theoretical model.

(6) The threshold of VCR under the condition $\beta n = 1$ is absent.

(7) The VCR spectrum is limited in principle from the short-wave side by the following conditions stipulated by the medium structure:

(a) the presence of bound charges in the medium;

(b) the binding energy of electrons in an atom determining the short-wave boundary of the spectrum; and

(c) the interatomic distance must be much smaller than the wavelength for the short-wave boundary of the spectrum.

Therefore, the mechanism proposed here does not contradict the basic laws, gives a more profound idea of the Vavilov–Cherenkov effect, and opens possibilities for understanding of its peculiarities and restrictions.

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