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Radiation from Uniformly Moving Sources (Vavilov–Cherenkov Effect, Transition Radiation, and Some Other Phenomena)[1]

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Abstract—The radiation produced by uniformly moving sources (the Vavilov–Cherenkov effect, the transition radiation, and some other phenomena) is discussed. This area of physical research originated in the Lebedev Physical Institute of the Russian Academy of Sciences and now represents an integral part of modern physics.

1. INTRODUCTION

During my long life, I have worked in many fields of science, which is typical of theoretical physicists. For the topic of this lecture, I could choose between the theory of superconductivity, astrophysics of cosmic rays, and radiation of uniformly moving sources. I choose the latter for two reasons. The first is that I love this area of research. Of course, the word "love" is not often used in scientific literature, but this is only a tribute to conventional style. In fact, in science, as in everyday life, we all love certain things and dislike some others. I love the problems concerned with the radiation of uniformly moving sources, because my first scientific results are related to this subject and remind me of my youth. The second reason for choosing this lecture topic is that the radiation from uniformly moving sources represents a basically Russian and, in addition, academic area of research. Indeed, the brightest phenomenon in this area, namely, the Vavilov–Cherenkov (V–Ch) effect, was discovered by S.I. Vavilov and P.A. Cherenkov in 1934 [1, 2]. The effect was interpreted by I.E. Tamm and I.M. Frank in 1937 [3]. The transition radiation was first considered by I.M. Frank and myself in 1945 [4]. All the aforementioned authors worked at the Lebedev Physical Institute and all of them were members of the Academy of Sciences of the USSR. In 1958, I.E. Tamm, I.M. Frank, and P.A. Cherenkov received the Nobel Prize in Physics for the discovery and interpretation of the V–Ch effect (Vavilov died in 1951 at less than sixty years of age, and the Nobel Prize could not be given posthumously).

2. THE VAVILOV–CHERENKOV EFFECT

In the framework of its own, somewhat narrowed interpretation, the V–Ch effect is as follows: an electric charge (e.g., an electron) moving in a medium with a constant velocity $\mathbf{v}$ emits electromagnetic waves (light) with a continuous spectrum and with a specific angular distribution. Radiation at a cyclic frequency ω occurs only if the velocity of the charge $\mathbf{v}$ exceeds the phase velocity of light in the transparent medium under consideration, $v_{ph} = c/n(\omega)$:

$$v > \frac{c}{n(\omega)}, \qquad (1)$$

where $n(\omega)$ is the refraction index for light at the frequency ω in the medium and c is the velocity of light in vacuum. The aforementioned specificity of the angular distribution of the radiation consists in that the wave vector of the emitted waves $\mathbf{k}$ and the velocity $\mathbf{v}$ make an angle θ_0 characterized by the formula

$$\cos\theta_0 = \frac{c}{n(\omega)v}. \qquad (2)$$

Results (1) and (2) can be obtained by applying the Huygens principle: every point on the path of a charge moving uniformly along a straight line with a velocity v represents a source of a spherical wave, which is emitted at the instant of the charge passage through this point (Fig. 1). Under condition (1), the spheres have a common envelope in the form of a cone whose vertex coincides with the instantaneous position of the charge, while the angle θ_0 is determined by Eq. (2).

If the dispersion, i.e., the dependence of n on ω, is ignored, the angle θ_0 is the same for all frequencies ω, and the radiation has a sharp wave front forming a cone with an angle of $\pi - 2\theta_0$ and with the charge (source) at its vertex (see Fig. 1). This cone is similar to the Mach cone, which characterizes a shock wave accompanying supersonic motion of a source (bullet, missile, airplane, or rocket) in air or in another medium. In this case, the role of the phase velocity of light $v_{ph} = c/n$ involved in expressions (1) and (2) is played by the velocity of the shock wave or the velocity of sound u. Since the dispersion of sound, i.e., the dependence of its velocity u on

[1] This lecture was given by V.L. Ginzburg upon receiving the Lomonosov Large Gold Medal, the highest prize awarded by the Russian Academy of Sciences. The lecture was published in *Physics–Uspekhi* **39** (10), 973 (1996).

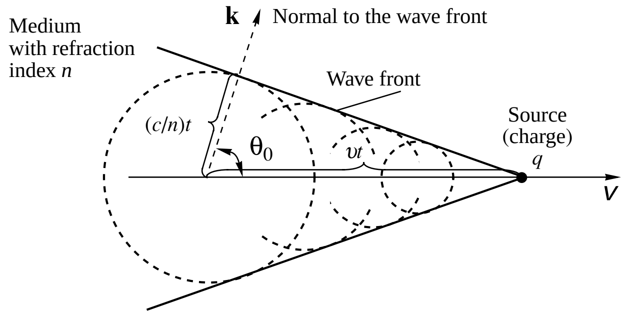

Fig. 1. Formation of the Vavilov–Cherenkov effect: $(c/n)t$ is the path length traveled by light within the time t and $vt = [c/(n\cos\theta_0)]t$ is the path length traveled by the charge (source) within the same time.

frequency, is usually very small, the hydrodynamic (acoustic) wave front at the Mach cone surface is sharp and is often observable (e.g., at the passage of a supersonic airplane).

Thus, V–Ch radiation represents an electrodynamic (optical) analog of the well-known (since the nineteenth century) acoustic phenomenon. Why, then, was V–Ch radiation not discovered and explained only as late as only about 60 years ago? Of course, this could have happened earlier, but, on the whole, the delay is not accidental. First, the observation of the V–Ch effect in a relatively pure form requires a beam of relativistic or nearly relativistic charged particles. Such beams were obtained in only the 1930s (when the first accelerators were built). Second, in electrodynamics (unlike hydrodynamics and acoustics), the motion of sources (charges) is primarily and most commonly considered in vacuum. Since the velocity of particles v is always smaller than the velocity of light $c = 3 \times 10^{10}$ cm s^{-1} (here, we do not consider the hypothetical and, most likely, nonexistent supraluminal particles, i.e., tachyons), the V–Ch effect in vacuum is impossible. Though here some reservations are appropriate (see, e.g., Sect. 9 in [5] and [6, 7]), on the whole, the existence of the former statement that “a uniformly moving charge does not emit radiation” is quite understandable.

Presumably, this dogma did not allow one to predict the V–Ch effect earlier. Actually, however, such a prediction was made by the well-known English physicist Heaviside in 1888 [8], but, at that time, even the electron had not been discovered and no fast particles moving in a dielectric could be imagined to exist in reality. Therefore, Heaviside’s idea was forgotten and was not again brought to light until as late as 1974 [9, 10]. Another precursor of the Tamm and Frank theory was the calculation performed by the well-known German physicist Sommerfeld [11], but Tamm and Frank became acquainted with it only after the termination of their work [3]. In 1904, Sommerfeld considered a uniform motion of a charge in a vacuum and made the conclusion that, at a supraluminal velocity $v > c$, the charge emits radiation. However, from the special relativity theory, which appeared within a year (in 1905), it followed that the motion of a charge with a velocity higher than c is impossible, and the work by Sommerfeld was forgotten as well.[2] Within the next 30 years, neither Sommerfeld nor any other physicists tried to consider the motion of a charge in a medium instead of the vacuum.

Precisely this idea was put forward by I.E. Tamm and I.M. Frank [3]: they calculated the radiation from a charge q moving with a constant velocity $\mathbf{v}$ in a medium with a refraction index $n(\omega)$. As a result, they formally derived expression (2) and obtained the radiation intensity (power) per unit time (i.e., within a path length equal to v):

$$\frac{dW}{dt} = \frac{q^2 v}{c} \int\limits_{c/[n(\omega)v] \le 1} \left(1 - \frac{c^2}{n^2(\omega)v^2}\right)\omega d\omega. \qquad (3)$$

Here, the integration is performed over all frequencies satisfying condition (1). Tamm and Frank sent a reprint of their paper [3] to Sommerfeld and, in response, received a letter dated May 8, 1937, which arrived through Austria (fascists were already in power, and it was difficult to write a letter directly to the USSR). In this letter, Sommerfeld wrote: “I never thought that my calculations of 1903 may find any physical application. This case proves that the mathematical part of the theory experiences a change of physical concepts.”[3]

The prehistory of the discovery of the V–Ch effect is described in more detail in the book written by Frank [14]. The development of the theory has been considered above. As for the experiment, the V–Ch radiation had actually been observed by Pierre and Marie Curie in bottles with radium salt solutions. Today, the blue glow of water, which mainly represents the V–Ch radiation, can be observed by excursionists when they are shown a nuclear reactor immersed in a water tank. The radiation from fluids irradiated with gamma rays was studied by the French scientist Mallet in 1926–1929. However, before Vavilov and Cherenkov, no one understood that this phenomenon was related to a new effect rather than to some kind of luminescence under the effect of gamma rays.

[2] Note that, from relativity theory, it follows (without considering tachyons) that the velocity c is limiting for a single charge (when $v \longrightarrow c$, the mass of the particle $m_0/\sqrt{1 - v^2/c^2}$ tends to infinity). However, a source of radiation (for example, a source consisting of many particles) may have any velocity (see [5–7]). I do not discuss this problem in this lecture, although it is of a certain interest.

[3] This letter is fully reproduced in *Recollections of I.E. Tamm* (see p. 120 in [12]). Sommerfeld also mentioned that, as a foreign member of the Academy of Sciences of the USSR, he received some of the Russian academic literature. Presumably, he was referring to the *Doklady Akademii Nauk SSSR* (*Doklady Physics*). It is a pity that today’s foreign members of the Russian Academy of Sciences receive nothing [13].

Experiments suggested by Vavilov and carried out by Cherenkov began with the observation of the luminescence of uranyl salt solutions under the effect of gamma rays. The experiments used an original method of measurement that was developed by Vavilov and his coworkers on the basis of using a dark-adapted human eye [14, 15]. By accident, Cherenkov discovered that the fluid (sulfuric acid) glows even in the absence of salt dissolved in it. He decided that his thesis had failed [15]. However, Vavilov understood that the experiments revealed a glow of a nature different from luminescence. Vavilov and Cherenkov continued their measurements and finally obtained enough evidence to report on the discovery of a new phenomenon [1, 2]. Vavilov indicated [2] that the glow observed in the experiment was not caused by gamma rays but was related to the Compton electrons that appeared in the fluid as a result of their knocking-out by gamma rays. The subsequent observations by Cherenkov [16] were performed with the participation of Vavilov and Frank [14, 15]. They revealed some properties of the new radiation that allowed Tamm and Frank to determine its nature [3].

From the aforesaid, it is clear that Vavilov is the coauthor of the discovery of the V–Ch effect, and only the name "Vavilov–Cherenkov" should be used for it. I stress this point because, in our (Soviet) literature, other opinions can be found, ones which are considered wrong by all physicists knowing the actual facts (see [14, 15, 17, 18]). As for the name "Cherenkov effect," which is always used abroad and sometimes in Russia—it is a consequence of the actions of Vavilov himself: he first published only a small letter reporting on the effect [2] and then sent to the *Physical Review* a large paper describing the V–Ch effect in detail [19], but this paper was signed by Cherenkov alone.[4] I do not know why Vavilov did such a thing. Possibly, because of his noble nature, he did not want to eclipse his student. Unfortunately, Vavilov suffered from various kinds of malicious attacks as a physicist, as a person, and as a scientific administrator and President of the Academy of Sciences of the USSR. I believe that all this criticism was groundless, and this opinion has already been expressed by me in my previous publications (see pp. 391, 393 in [20] and also [21]).

The V–Ch effect has found wide application in physics (here, I do not mention its significance for the electrodynamics of continuous media and for physics as a whole). On the basis of the V–Ch effect, one can determine the velocity of a particle v by measuring the angle θ_0 (see Eq. (2)) or, from inequality (1), directly (in the absence of the effect) conclude that $v < c/n(\omega)$ (evidently, the refraction index $n(\omega)$ in a transparent medium may and should be considered to be known). In addition, since the radiation intensity is proportional to the square of the charge q of a particle (see Eq. (3)), one can easily distinguish particles with the elementary charge e (electrons, protons, etc.) from nuclei with charges Ze (where Z is the ordinal number of an element). Even for a helium nucleus ($Z = 2$), the radiation intensity is four times as high as that for hydrogen isotopes ($Z = 1$); for an iron nucleus ($Z = 26$), the intensity is 676 times higher that for protons with the same velocity. The so-called Cherenkov counters are widely used in accelerators and in high-energy physics as a whole [22, 23]. Specifically, the V–Ch effect is used in studying cosmic rays (the V–Ch radiation from a shower in the atmosphere) and in systems designed for observing high-energy neutrinos.

The theory of V–Ch radiation cannot be fully described in the framework of this lecture (for details, see [5–7, 14, 22, 24]), and I will dwell only on several problems that are subjects of my own former investigations.

In 1940, Mandel'shtam, acting as an official opponent to Cherenkov's doctoral thesis, noted that the V–Ch effect should also be observed when a charge (source) moves not in a continuous medium but in a thin empty channel running through this medium. Physically, the idea is that the V–Ch radiation is formed not only on the very path of the charge but also near the path, at a distance of about the wavelength of the emitted light $\lambda = 2\pi c/[n(\omega)\omega]$. The corresponding radiation intensity was calculated by Frank and myself [25]. Naturally, this intensity decreases with increasing radius r of the empty channel, along the axis of which the charge moves. If we have $\sqrt{1 - v^2/c^2} \sim 1$, then, for $r/\lambda \lesssim 0.01$ (in optics, this means that $r \lesssim 5 \times 10^{-7}$ cm), the radiation is practically the same as that in the absence of the channel. Qualitatively, a similar situation occurs when the channel is replaced by a gap or when the charge moves near the boundary of a medium (a dielectric). This consideration is important because, in the course of the motion of the charge in a medium, its energy loss due to V–Ch radiation is relatively small; the predominant factor is the ionization loss, which is localized in the immediate vicinity of the trajectory. Therefore, in the case of motion in a channel, in a gap, or near a medium, the ionization loss is absent though the V–Ch radiation persists. For charges, this fact is important but not critical, while for the observation of the Doppler effect in a medium, where the motion of excited atoms is involved, the whole phenomenon can be observed only with the use of channels or gaps; otherwise, the atom breaks up. However, the Doppler effect may be observed (and was observed) in the case of the motion in a rarefied medium, in particular, in plasma.

Incidentlly, the analysis of the problem of radiation in the case of motion near a medium was used by me in

[4] Note that this paper [19] was initially sent to *Nature* but was rejected. This shows that the V–Ch effect seemed to be rather nontrivial at that time.

discussing various possibilities of microwave generation [26–28].

Now, I consider the methods of calculating the intensity of V–Ch radiation. Tamm and Frank [3] obtained expression (3) by solving the electrodynamics equations in a medium and defining the radiation intensity as the Poynting vector flux through a cylindrical surface surrounding the trajectory of the charge. Another method of calculation consists in the determination (on the basis of the same equations) of the force that decelerates the moving charge: the work of this force in a transparent medium is equal to the radiation energy given by Eq. (3). Such calculations were performed, for example, by Fermi [29], and they can be found in the book by Landau and Lifshits [30] (see § 115). Finally, there is a third method for calculating the same intensity (power) given by Eq. (3). It consists of calculating the energy of the electromagnetic field generated by the charge per unit time [31].

For this purpose, it is convenient to use the so-called Hamiltonian method. For a homogeneous isotropic stationary medium, it uses a series expansion of the vector potential **A** of the field (for more details, see, e.g., [5]):

$$\begin{cases} \mathbf{A}(\mathbf{r}, t) = \sum\limits_{\lambda, i = 1, 2} q_{\lambda i}(t)\mathbf{A}_{\lambda i}(\mathbf{r}); \\ \mathbf{A}_{\lambda 1} = \mathbf{e}_\lambda \sqrt{8\pi}\dfrac{c}{n}\cos(\mathbf{k}_\lambda \mathbf{r}), \\ \mathbf{A}_{\lambda 2} = \mathbf{e}_\lambda \sqrt{8\pi}\dfrac{c}{n}\sin(\mathbf{k}_\lambda \mathbf{r}), \end{cases} \tag{4}$$

where $\mathbf{e}_\lambda$ is the polarization vector ($e_\lambda = 1$) and $n = \sqrt{\varepsilon}$ is the refraction index (ε is the permittivity of the medium, and the latter is assumed to be nonmagnetic for simplicity). The transverse electromagnetic field under consideration has the form

$$\mathbf{E}_{\mathrm{tr}} = -\frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}, \quad \mathbf{H} = \mathrm{rot}\mathbf{A},$$

and the energy of this field is

$$\mathcal{H}_{\mathrm{tr}} = \int \frac{\varepsilon E_{\mathrm{tr}}^2 + H^2}{8\pi} dV = \frac{1}{2}\sum_{\lambda, i = 1, 2}(p_{\lambda i}^2 + \omega_\lambda^2 q_{\lambda i}^2), \tag{5}$$

where

$$p_{\lambda i} = \frac{dq_{\lambda i}}{dt}, \quad \omega_\lambda^2 = \frac{c^2}{\varepsilon}k_\lambda^2 \equiv \frac{c^2}{n^2}k_\lambda^2. \tag{6}$$

The field equation has the form

$$\Delta \mathbf{A} - \frac{\varepsilon}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = -\frac{4\pi}{c}\mathbf{j};$$

for a point charge q moving with a velocity **v**, the current density is $\mathbf{j} = q\mathbf{v}\delta[\mathbf{r} - \mathbf{r}_q(t)]$, where $\mathbf{r}_q(t)$ is the radius vector of the charge and δ is a delta function. With the substitution of expansion (4), the field equation takes the form

$$\begin{cases} \dfrac{d^2 q_{\lambda 1}}{dt^2} + \omega_\lambda^2 q_{\lambda 1} = \sqrt{8\pi}\dfrac{c}{n}(\mathbf{e}_\lambda \mathbf{v})\cos(\mathbf{k}_\lambda \mathbf{r}_q), \\ \dfrac{d^2 q_{\lambda 2}}{dt^2} + \omega_\lambda^2 q_{\lambda 2} = \sqrt{8\pi}\dfrac{c}{n}(\mathbf{e}_\lambda \mathbf{v})\sin(\mathbf{k}_\lambda \mathbf{r}_q). \end{cases} \tag{7}$$

Thus, the field equations are reduced to Eqs. (7) for the "field oscillators" $q_{\lambda i}(t)$. Integrating these equations and substituting the solution into Eq. (5), we obtain the field energy as the sum of the energies of all oscillators. For a charge uniformly moving along a straight line, we have $\mathbf{r}_q(t) = \mathbf{v}t$, and Eqs. (6) can be easily integrated, because they are equations for an oscillator oscillating under a harmonic force proportional to $\cos(\mathbf{k}_\lambda \mathbf{v}t)$ or $\sin(\mathbf{k}_\lambda \mathbf{v}t)$, i.e., oscillating with a frequency

$$\omega = \mathbf{k}_\lambda \mathbf{v} = k_\lambda v\cos\theta = \frac{\omega_\lambda n v}{c}\cos\theta. \tag{8}$$

At $\omega = \omega_\lambda$, a resonance takes place and the amplitudes $q_{\lambda i}$ increase with time; i.e., radiation is observed. Evidently, in a vacuum where $n = 1$, the frequency ω is always smaller than ω_λ (provided that $v < c$). This means that a charge moving uniformly in a vacuum does not emit any radiation. In a medium, however, the resonance (and, hence, the radiation) is possible. According to Eq. (8), the resonance condition is $(nv/c)\cos\theta = 1$, i.e., the V–Ch radiation condition (see Eq. (2)). The substitution of the solution for $q_{\lambda i}(t)$ into Eq. (5) yields the expression $\mathcal{H}_{\mathrm{tr}} = (dW/dt)t$, where dW/dt is determined by Eq. (3).

Thus, in the case under consideration, calculation by the Hamiltonian method is simple and self-evident. The character of this lecture allows me to note that precisely this simplicity, which I discovered by accident, encouraged me to switch to theoretical physics (I graduated from the Moscow State University in 1938 as an experimentalist in optics and believed that I should not work in theoretical physics because of the lack of mathematical talent). Of course, I considered the Hamiltonian method not with the aim of making the above comment. It is important that, unlike the two other methods mentioned above, the Hamiltonian method for calculating the radiation energy allows for an almost trivial generalization to the case of an anisotropic medium, i.e., to noncubic crystals or to a plasma in a magnetic field. In an anisotropic medium, the field should be decomposed into normal waves, which may propagate in the corresponding medium (in an isotropic medium, as in vacuum, degeneration takes place and the normal waves are reduced to waves $\mathbf{A}_{\lambda i}$ given by Eqs. (4)). Thus, one can easily consider the V–Ch effect in an anisotropic medium, the simplest example of which is a uniaxial crystal [32]. In this case, the V–Ch radiation forms two cones, which, in the general case, are not circular and have different polarizations (directions of the electric field in the waves). Experimental studies of the V–Ch effect in crystals were performed, in particular, by Zrelov [22].

Numerous publications in addition to those cited are concerned with different aspects of the theory of V–Ch radiation. They include the generalization to magnetic media, a detailed analysis of radiation in crystals, the role of boundaries, etc. (see [5–7, 14, 22, 33, 34] and the literature cited there). I specially note the study of the role of absorption [29, 35] and the consideration of V–Ch radiation not from charges but from various dipoles and multipoles (see [5–7, 14] where references to original publications are given). The problem of the V–Ch radiation from multipoles has not been completely investigated [5–7]. Presumably, this can be explained by the fact that the known particles have rather small magnetic moments (not to mention other multipoles), and the radiation associated with these moments is also very weak and of no practical interest. As for the radiation from a magnetic charge (a monopole), it should be considerable, but such monopoles have never been observed; possibly, they do not exist in nature.

For reasons of space, it is impossible to dwell here on the problems listed above and on all the experiments using V–Ch radiation (see [22, 23]). However, the quantum interpretation of the V–Ch effect seems to be worth discussing.

3. THE QUANTUM THEORY OF THE VAVILOV–CHERENKOV EFFECT

The classical theory of the V–Ch effect, which was discussed above, is sufficiently accurate in the optical part of the spectrum. Nevertheless, proceeding from methodical considerations, it is expedient to consider more closely the quantum theory of the effect [36] (see also [5–7], 14]).

How should the absence of radiation from a charge (or some other source possessing no eigenfrequency) uniformly moving in vacuum be explained in quantum terms? For this purpose, it is sufficient to use the energy and momentum conservation laws in application to the emission of a photon by a particle:

$$\begin{cases} E_0 = E_1 + \hbar\omega, \quad E_{0,1} = \sqrt{m^2c^4 + c^2p_{0,1}^2}, \\ \mathbf{p}_0 = \mathbf{p}_1 + \hbar\mathbf{k}, \quad k = \dfrac{\omega}{c}, \quad \mathbf{p}_{0,1} = \dfrac{m\mathbf{v}_{0,1}}{\sqrt{1 - v_{0,1}^2/c^2}}, \end{cases} \tag{9}$$

where $E_{0,1}$ and $\mathbf{p}_{0,1}$ are the energy and momentum of a charge with a mass at rest m before the emission (subscript 0) and after the emission (subscript 1) of a photon with an energy $\hbar\omega$ and momentum $\hbar\mathbf{k} = (\hbar\omega/c)(\mathbf{k}/k)$. One can easily verify that Eqs. (9) have no solution for $v < c$ (with $\omega > 0$); i.e., the photon emission is impossible (see Eq. (11) with $n = 1$).

To consider the problem of radiation from a source in a medium, it is necessary to know only: what the energy and momentum of the radiation are in this case, because the energy of a particle $E = \sqrt{m^2c^4 + c^2p^2}$ does not change in the medium. This question is not that simple (see Sect. 13 in [5]), but it can be solved rather simply (and correctly) at the intuitive level. Indeed, in a stationary and time-invariant medium, its presence does not affect the frequency ω, and the wavelength is $\lambda = \lambda_0/n$, where $\lambda_0 = 2\pi c/\omega$ is the wavelength in vacuum. The wave number is $k = 2\pi/\lambda = \hbar\omega n/c$. Taking this into account, instead of Eqs. (9), we write

$$\begin{cases} E_0 = E_1 + \hbar\omega, \quad E_{0,1} = \sqrt{m^2c^4 + c^2p_{0,1}^2}, \\ \mathbf{p}_0 = \mathbf{p}_1 + \hbar\mathbf{k}, \\ k = \dfrac{\hbar\omega n(\omega)}{c}, \quad \mathbf{p}_{0,1} = \dfrac{m\mathbf{v}_{0,1}}{\sqrt{1 - v_{0,1}^2/c^2}}. \end{cases} \tag{10}$$

Solving these equations with respect to ω and θ_0, where θ_0 is the angle between $\mathbf{v}_0$ and $\mathbf{k}$, we obtain

$$\cos\theta_0 = \frac{c}{n(\omega)v_0}\left[1 + \frac{\hbar\omega(n^2 - 1)}{2mc^2}\sqrt{1 - \frac{v_0^2}{c^2}}\right], \tag{11}$$

$$\hbar\omega = \frac{2(mc/n)(v_0\cos\theta_0 - c/n)}{(1 - 1/n^2)\sqrt{1 - v_0^2/c^2}}. \tag{12}$$

Under the condition

$$\frac{\hbar\omega}{mc^2} \ll 1 \tag{13}$$

(or under a more accurate inequality evident from Eq. (11)), expression (11) is transformed into classical expression (2). This result should be expected, because condition (13) evidently corresponds to the classical limit (it is always valid when $\hbar \longrightarrow 0$). In the classical limit, the recoil (the change in the momentum $\mathbf{p}_0$ of the particle) due to the emission of a photon in the medium with a momentum $\hbar\mathbf{k}$ is ignored. As was mentioned above, from Eq. (12) it follows that emission ($\omega > 0$) is possible only when $v_0 > c/n$ (because $\cos\theta_0 \le 1$). In the classical limit, when the result (see Eq. (2)) does not depend on $\hbar$, the quantum calculation is only of methodical significance; it may be convenient but is not obligatory. This corresponds to the real situation, and the conservation laws can be formulated in the classical region as well; it is only necessary to take into account the relation between the emitted electromagnetic energy $\mathcal{H}_{tr}$ and the momentum of the radiation. The corresponding simple calculations are given in [5–7].

Evidently, the radiation intensity can also be calculated in quantum terms by generalizing Eq. (3) [36].

In the optical region, which is the only one dealt with in the applications of the V–Ch effect, even for electrons the ratio $\hbar\omega/mc^2 \sim 10^{-5}$ is small; i.e., the quantum corrections are insignificant. In light of this, Landau, when he became aware of my work [36] published in 1940, noted that it is of no interest (see p. 380 in [20]). From the aforesaid, it is clear that this conclusion was justified, and this was characteristic of Landau: his critical comments were usually correct. However, a different approach or method of obtaining a known result proves to be useful in applications to other problems. Such an example concerning different ways of calculating the V–Ch radiation power given by Eq. (3) was mentioned above. It was found that a similar situation arises in the case of applying the conservation laws to the analysis of the radiation in a medium. Precisely the application of conservation laws proves to be fruitful in studying the Doppler effect in a medium.

4. THE DOPPLER EFFECT IN A MEDIUM

The sources discussed above (specifically, charges) possess no eigenfrequency. Another important case is a source without a charge or any time-invariable multipole moment but with an eigenfrequency ω_0. A classical example is an oscillator, and a quantum example is an atom, which, at a certain transition, radiates a frequency ω_{00} (this frequency refers to the frame of reference in which the source is at rest).

If such a source moves with a constant velocity **v** (in the laboratory frame of reference) in a vacuum, the frequency of the waves produced by it is estimated in the laboratory frame of reference by the formula

$$\omega(\theta) = \frac{\omega_{00}\sqrt{1-v^2/c^2}}{1-(v/c)\cos\theta} = \frac{\omega_0}{1-(v/c)\cos\theta}, \qquad (14)$$

where θ is the angle between the wave vector **k** (the observation direction) and the velocity **v**; the frequency ω_0 in Eq. (14) represents the oscillation frequency in the laboratory frame of reference. The change in the frequency of waves produced by a moving source is called the Doppler effect. This effect also occurs in acoustics, as well as for waves of any nature.

Now, let us consider a transparent medium (with a refraction index $n(\omega)$), which is at rest in the same laboratory frame of reference, and an oscillator or an atom (molecule) moving in it. The fact that a source moving through a continuous medium may fail is insignificant, because a channel or a gap in the medium can be used (see above).

In the presence of the medium, Eq. (14) should be replaced by the expression [37, 14]

$$\omega(\theta) = \frac{\omega_{00}\sqrt{1-v^2/c^2}}{|1-(v/c)n(\omega)\cos\theta|} = \frac{\omega_0}{|1-(v/c)n(\omega)\cos\theta|}. \qquad (15)$$

This formula can be obtained using the following general rule: by replacing the velocity of light in vacuum by the phase velocity in the medium $c/n(\omega)$ (in the radicand of $\sqrt{1-v^2/c^2}$, the quantity c should not be replaced by c/n, because this root is associated with the time dilation for the moving source and is unrelated to the radiation process). Expression (15) can also be derived formally by solving the field equations for a moving source. In this expression, the appearance of the absolute value is nontrivial (its necessity is evident from the requirement that the frequency should be positive). If the motion is subluminal (i.e., $v < c/n$) or if it is supraluminal but occurs outside the cone defined by Eq. (2), i.e., under the condition that

$$\frac{v}{c}n(\omega)\cos\theta < 1, \qquad (16)$$

the conventional normal Doppler effect takes place. Note that, in this case, the so-called complex Doppler effect, which is caused by the dispersion, i.e., by the dependence of n on ω, is also possible [37, 14].

If the motion is supraluminal (condition (1) is satisfied), then, in the angular region determined by the formula

$$\frac{v}{c}n(\omega)\cos\theta > 1, \qquad (17)$$

Eq. (15) without the absolute value sign leads to negative frequency values. The radiation in region (17), i.e., inside the cone defined by Eq. (2) (often called the Cherenkov cone (Fig. 2)), is called the anomalous Doppler effect. With allowance for the dispersion, the whole picture proves to be complicated (every frequency has its own cone and, if the dependence of n on ω is nonmonotone, several cones). Here, we limit our consideration to the case without dispersion: $n(\omega) = n =$ const. Then, according to Eq. (15), on the Cherenkov cone surface where $(v/c)n\cos\theta = (v/c)n\cos\theta_0 = 1$, the frequency is $\omega \longrightarrow \infty$, and this occurs on both sides of the cone surface (at $\theta \longrightarrow \theta_0$). From Eq. (15), no other inferences can be drawn, and the difference between the normal and anomalous Doppler effect does not seem to be significant.

However, it was found that the quantum approach (or, more precisely, the use of the energy and momentum conservation laws) reveals a very important feature of the anomalous Doppler effect [38, 5–7, 14]. Let us assume that the source is a "system" (atom) with two levels: the lower level 0 and the upper level 1 (Fig. 3).

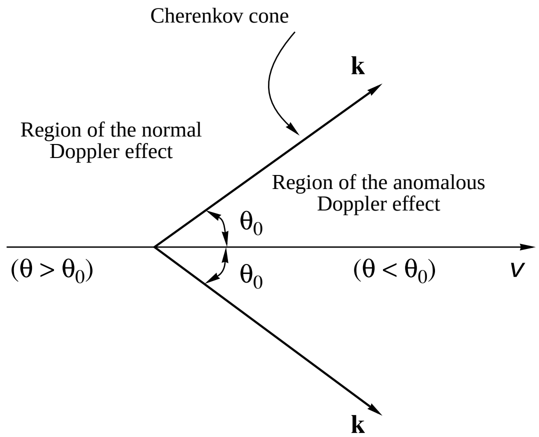

Fig. 2. Regions of the normal ($\theta > \theta_0$) and anomalous ($\theta < \theta_0$) Doppler effects.

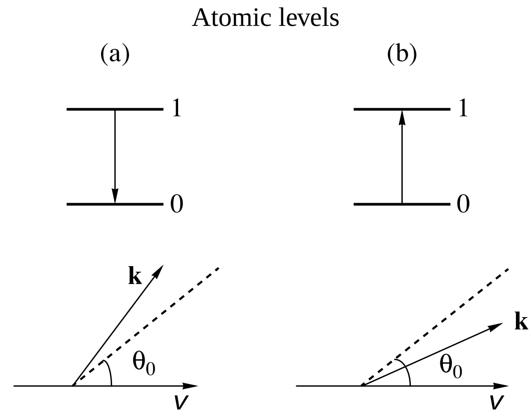

Fig. 3. Transitions between atomic levels 0 and 1 in the cases of the (a) normal and (b) anomalous Doppler effects.

Then, using conservation laws of type (10), one only has to modify the expression for the energy of the source by taking into account the presence of the internal degrees of freedom (levels). This energy has the form

$$E_{0,1} = \sqrt{(m + m_{0,1})^2 c^4 + c^2 p_{0,1}^2}, \tag{18}$$

where $(m + m_0)c^2 = mc^2 + W_0$ is the total energy of the system (atom) in the lower state 0 and $(m + m_1)c^2 = mc^2 + W_1$ is the corresponding energy in the upper state 1. Since $W_1 > W_0$, in the case of the transition $1 \longrightarrow 0$, the atom at rest emits radiation with the frequency $\omega_{00} = (W_1 - W_0)/\hbar$.

Using the conservation laws in classical limit (13), we arrive at Eq. (14) and, in the case of an exact calculation [38], to a somewhat more complex expression containing terms on the order of $\hbar\omega/mc^2$. However, not the quantum corrections but the following unexpected situation proves to be significant. Tracing the signs (this is simple algebra), one can easily see that, in the region of the normal Doppler effect, the atom, as in vacuum, performs a transition from the upper level 1 to the lower level 0 (the direction of the transition is determined from the requirement that the energy of the emitted photon, $\hbar\omega$, be positive, i.e., from the condition $\omega > 0$). By contrast, in the region of the anomalous Doppler effect, the emission of a photon is accompanied by the excitation of the atom: it performs the transition from level 0 to level 1 (Fig. 3). In this case, the energy is taken from the kinetic energy of the translational motion.

Thus, in the case of supraluminal motion ($v > c/n$), which is the only case allowing the anomalous Doppler effect, the initially nonexcited atom (in the lower state 0) becomes excited (changes to level 1), simultaneously emitting a photon within the Cherenkov cone. The excited atom emits radiation (upon the transition $1 \longrightarrow 0$) outside the Cherenkov cone, i.e., at the angles $\theta > \theta_0$. As a result, in the course of the supraluminal motion, the atom is continuously excited and emits radiation. For the classical oscillator model, this means that the oscillator is excited all the time. The anomalous Doppler effect is quite important for plasma physics. On the whole, in plasma, the V–Ch effect and the notions and analogies related to it play an important role. This fact was stressed by Tamm in his Nobel lecture [17]. There, he also put forward the assumption that the acoustic analog of the anomalous Doppler effect known in optics plays an important part in the analysis of vibrations that accompany the supersonic motion of an airplane (the so-called flutter).

I think that, without the quantum consideration, it would be difficult to reveal the aforementioned feature of the anomalous Doppler effect [38] (more precisely, as follows from the above, not the quantum approach but the application of the conservation laws is important). The testing of the result and further progress is made possible by means of a classical or quantum calculation of the radiation response for a source moving in a medium. Specifically, for an oscillator moving in a medium, one can determine the effect of the radiation force on the oscillations of the oscillator (see [39], [5], ch. 7). The wave radiation in the region outside the Cherenkov cone (i.e., in the case of the normal Doppler effect) was found to slow down the oscillations. By contrast, the radiation directed inside the Cherenkov cone, i.e., corresponding to the anomalous Doppler effect, enhances the oscillations of the oscillator, i.e., excites it. This result agrees well with the above quantum consideration.

Note that a number of publications developing the cited work [39] and also some other publications in this area of research belong to B.E. Nemtsov [40], the well-known governor of the Nizhni Novgorod region and a former talented theoretical physicist.

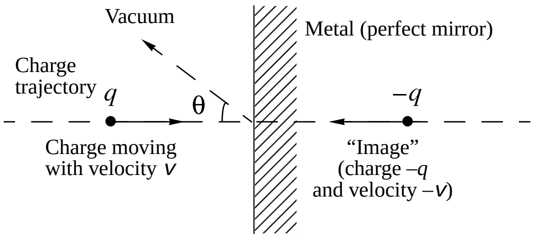

Fig. 4. Transition radiation from a charge q crossing the vacuum–metal boundary.

The above consideration also clarifies the mechanism of excitation of uniformly accelerated "detectors" [41, 7]. As is known, the latter problem has been much discussed in the literature (for references, see [41]) in connection with studies of the radiation from black holes and uniformly accelerated systems (acceleration radiation).

5. TRANSITION RADIATION AT A BOUNDARY BETWEEN TWO MEDIA

In the course of uniform rectilinear motion of a source without an eigenfrequency (a charge or a multipole), radiation in the medium, i.e., V–Ch radiation, occurs only at a supraluminal velocity defined by condition (1). However, in this case, the medium is assumed to be homogeneous and time-invariant. If the medium is inhomogeneous and/or varies with time, some radiation is also possible from a source uniformly moving with a subluminal velocity. This radiation, the possibility of which was first considered in 1945 [4], is called transition radiation.

The simplest case of transition radiation is as follows: a charge uniformly moving along a straight line with any velocity crosses a boundary between two media. The point of intersection of the charge trajectory with the boundary becomes a source of transition radiation. This conclusion is most evident in the situation where the charge is incident from the vacuum on a metal surface (with a high conductivity), which plays the role of a perfect mirror (Fig. 4). From electrodynamics, it follows that, under such conditions, the field of the charge in vacuum is a sum of the fields of the charge q moving in the vacuum in the absence of the mirror and a charge $-q$ moving in the mirror toward the charge q (i.e., with the velocity $-v$). The charge $-q$ is called the "image" of the charge q. When charge q crosses the metal boundary, it falls into a conducting medium and ceases to produce a field in the vacuum; the image $-q$ also disappears. Thus, from the viewpoint of an observer in the vacuum, the annihilation of the pair of charges q and $-q$ occurs at the instant of crossing the boundary. From the same electrodynamics, it is known that annihilation, as well as any acceleration of charges (in the case under study, both charges q and $-q$ are abruptly stopped at the boundary), should be accompanied by a radiation. This is the transition radiation for the case under consideration.

For a perfect mirror, the energy radiated into the vacuum is expressed as

$$W_1(\omega,\theta) = \frac{q^2 v^2 \sin^2\theta}{\pi^2 c^3 [1-(v^2/c^2)\cos^2\theta]^2},$$
$$W_1(\omega) = 2\pi\int W_1(\omega,\theta)\sin\theta\, d\theta \qquad (19)$$
$$= \frac{q^2}{\pi c}\left[\frac{1+v^2/c^2}{2v/c}\ln\left(\frac{1+v/c}{1-v/c}\right)-1\right].$$

In the ultrarelativistic limit (as $v \longrightarrow c$), we have

$$W_1(\omega) = \frac{q^2}{\pi c}\ln\frac{2}{1-v/c} = \frac{2q^2}{\pi c}\ln\frac{2E}{mc^2},$$
$$E = \frac{mc^2}{\sqrt{1-v^2/c^2}} \gg mc^2. \qquad (20)$$

Formulas (19) and (20) are derived rather easily [5–7, 42]. However, in the general case of two media characterized by complex permittivities ε_1 and ε_2, the calculations are cumbersome [4, 5, 42], and I do not present here even their results. It should only be noted that the aforementioned "backward" transition radiation (see Fig. 4) is of no practical interest. Presumably, it may account for the optical glow of anticathodes of X-ray tubes. In principle, this transition radiation may be used for measuring the particle energy E, because this quantity is involved in Eq. (20) for the emitted energy. However, in Eq. (20), the dependence on E is logarithmic while the absolute value of the energy W_1 is fairly small. It was found (in 1959; [43, 44]) that, for ultrarelativistic particles, it is expedient to consider the "forward" transition radiation, i.e., the radiation in the direction of the particle velocity, for example, when the particle passes from a substance into the vacuum. In this case, high-frequency radiation should be emitted as well, and the total radiation energy of a particle with a charge q and mass m is

$$W_2 = \int W_2(\omega)d\omega = \frac{q^2\omega_p}{3c}\frac{E}{mc^2}, \qquad (21)$$

where ω_p is the plasma frequency of the substance (at high frequencies, all substances are equivalent to a plasma with a permittivity

$$\varepsilon = n^2 = 1-\frac{\omega_p^2}{\omega^2}; \quad \omega_p^2 = \frac{4\pi e^2 N}{m_e},$$

where N is the electron concentration in the substance and e and m_e are the charge and mass of an electron).

The radiation energy W_2 is proportional to the particle energy E. Hence, by measuring W_2 one can determine E, which is important for high-energy particle physics. Here, it should be noted that the use of the V–Ch effect for the energy measurements at high energies is ineffective. The point is that, in the ultrarelativistic region where $v \longrightarrow c$, the Cherenkov angle θ_0 (see Eq. (2)) and the radiation intensity (Eq. (3)) are almost insensitive to the particle energy $E = mc^2/\sqrt{1 - v^2/c^2}$. The measurement of the energy of the "forward" transition radiation W_2 is used as a basis for so-called transition counters, which have found wide application in high-energy particle physics [45, 46]. To avoid any misunderstanding, it should be noted that, since for a single boundary the energy W_2 (Eq. (21)) is rather small, the transition counters should use a "sandwich" of many sheets (plates) of a material with, e.g., air-filled gaps between them. The presence of many boundaries imposes certain limitations on the structure of such a counter. This fact involves some rather interesting physics (the consideration of the zone of the radiation formation) (see [5–7, 14, 42]).

6. TRANSITION RADIATION (THE GENERAL CASE). TRANSITION SCATTERING. TRANSITION BREMSSTRAHLUNG

The transition radiation that occurs at the intersection of a sharp interface represents the simplest case. In the general case, the transition radiation always appears when a source (charge) uniformly moves in an inhomogeneous and/or nonstationary medium or near it. In addition to the aforementioned situation with the "annihilation" of the source and its image, the transition radiation can be interpreted in a more general way. As an example, let us consider an isotropic transparent medium characterized by a refraction index n. Then, in the general case, the phase velocity of light in the medium is $v_{ph} = c/n(\omega, \mathbf{r}, t)$, where $\mathbf{r}$ represents the coordinates and t is time (evidently, in a homogeneous stationary medium, we have $n(\omega, \mathbf{r}, t) = n(\omega)$). The light radiation from a charge moving with a velocity v is governed by the ratio $v/v_{ph} = vn/c$. In vacuum, $n = 1$ and, at v = const, the radiation is absent (we assume that $v < c$); the radiation is possible only with the acceleration of the charge, i.e., when $v = v(t)$ and the acceleration is $w = dv/dt \neq 0$. In the medium, in the case of a uniform rectilinear motion with v = const and $w = 0$, the ratio vn/c still may change because of the dependence of n on $\mathbf{r}$ and/or on t. Precisely this is the transition radiation, provided that the refraction index $n(\omega, \mathbf{r}, t)$ varies at the charge site or near it (within the zone of the radiation formation).

In the case of crossing a boundary between two media, the index n changes at this boundary. Another version involves any inhomogeneous medium (emulsion, plasma in an inhomogeneous magnetic field, etc.). One more possibility is of interest but not really practical: a charge uniformly moves in a homogeneous medium but, at some instant $t = t_0$ (or within some interval of time near the instant t_0), the refraction index changes in the whole medium, for example, because of the compression of the medium. Then, the point where the charge occurs at the instant t_0 plays (although not literally) a role similar to that of a boundary between two media [47, 42]. An important case of an inhomogeneous medium is a periodically inhomogeneous one, for example, a stack of plates used in transition counters [48, 42]. The transition radiation arising under such conditions is sometimes called resonance transition radiation or transition scattering. When a charge moves through a periodically inhomogeneous medium (a sine medium (see Eq. (22) below), a medium consisting of a set of sharp boundaries, etc.), one can say (from the charge standpoint) that a permittivity (refraction index) wave is incident on the charge. The scattering of this wave from the charge gives rise to transition radiation. However, the use of the term "transition scattering" would be not justified without the presence of this effect for a charge at rest. In this case, the term "transition radiation" seems to be inappropriate, while the term "transition scattering" fits the situation. For example, the effect occurs when a permittivity wave is incident on a charge q at rest (a fixed charge), and, as a result, an electromagnetic wave propagates (is scattered) from the charge (Fig. 5).

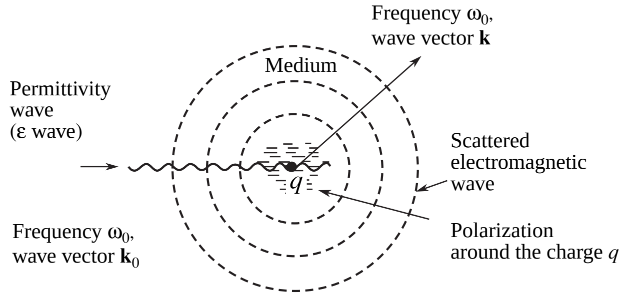

Fig. 5. Schematic diagram of the transition scattering of a permittivity wave from a stationary (fixed) charge q.

This result can also be easily understood without the general theory of transition radiation. For example, let us consider an isotropic transparent medium with a permittivity $\varepsilon = n^2$. If an acoustic wave propagates in such a medium, the density of the latter has the form $\rho = \rho^{(0)} + \rho^{(1)}\sin(\mathbf{k}_0\mathbf{r} - \omega_0 t)$, where $\mathbf{k}_0$ and ω_0 are the wave vector and the frequency of the acoustic wave, respectively. The variation of the density ρ is accompanied by a variation of ε, which gives rise to a permittivity wave:

$$\varepsilon(\mathbf{r}, t) = \varepsilon^{(0)} + \varepsilon^{(1)}\sin(\mathbf{k}_0\mathbf{r} - \omega_0 t), \qquad (22)$$

where $\varepsilon^{(0)}$ is the permittivity in the absence of the acoustic wave and $\varepsilon^{(1)}$ is the variation in ε due to the density variation. Evidently, a permittivity wave may be caused not only by an acoustic wave but also by some other factor, e.g., a longitudinal plasma wave.

Let us place a fixed or an infinitely heavy charge q in the medium. An electric field $\mathbf{E}$ and an induction $\mathbf{D}$ =

$\varepsilon\mathbf{E}$ appear around the charge. If no wave is present, the field $\mathbf{E}$ is a Coulomb one:

$$\mathbf{E}^{(0)} = \frac{q\mathbf{r}}{\varepsilon^{(0)} r^3}, \quad D^{(0)} = \varepsilon^{(0)}\mathbf{E} = \frac{q\mathbf{r}}{r^3}. \qquad (23)$$

In the presence of wave (22), in the first approximation (under the condition $|\varepsilon^{(1)}| \ll \varepsilon^{(0)}$), an additional polarization arises:

$$\delta\mathbf{P} = \frac{\delta\mathbf{D}}{4\pi} = \frac{\varepsilon^{(1)}}{4\pi}\mathbf{E}^{(0)}\sin(\mathbf{k}_0\mathbf{r} - \omega_0 t). \qquad (24)$$

Such a polarization, which has no spherical symmetry (at $k_0 \neq 0$), gives rise to an electromagnetic wave of frequency ω_0 diverging from the charge (see Fig. 5). The wave number of this wave is $k = 2\pi/\lambda = (\omega_0/c)\sqrt{\varepsilon^{(0)}}$. If the permittivity wave is caused by an acoustic wave (as we assumed above), we have $k \ll k_0 = \omega_0/u$, where u is the velocity of sound (evidently, we assume that $u \ll c/\sqrt{\varepsilon^{(0)}}$).

The arising electromagnetic wave can be interpreted as a scattered one in the sense common to other types of scattering, for example, the Thomson scattering of an electromagnetic wave from an electron at rest (in this case, at rest means without taking into account the effect of the incident wave). If the medium is an isotropic plasma and the incident wave is a longitudinal (plasma) wave, the transition scattering under discussion represents a transformation of a longitudinal wave into an electromagnetic (transverse) one. This suggests that the transition scattering plays an important part in plasma physics, which actually is true [5–7, 42]. Let us illustrate this by an example. A longitudinal wave in plasma (its frequency is close to $\omega_p = \sqrt{4\pi e^3 N/m_e}$) contains some electric field and also involves a variation in ε. Thus, when a longitudinal wave propagates in plasma, the plasma particles (electrons and ions) are under the simultaneous effects of the electric field wave and the permittivity wave. Electrons of the plasma oscillate in the electric field and, hence, are sources of scattered electromagnetic waves (the so-called Thomson scattering), whose intensity is inversely proportional to the square of the mass of the scattering particle m. Therefore, the Thomson scattering from ions is characterized by an intensity that is $(m_i/m_e)^2$ times smaller than the intensity of the scattering from electrons (m_e is the electron mass and m_i is the ion mass). Hence, even in the case of Thomson scattering from the lightest ions, namely, protons with a mass $m_p = 1836m_e$, its intensity is $(1836)^2 \approx 3.4 \times 10^6$ times smaller than that in the case of scattering from electrons. By contrast, transition scattering in the first approximation does not depend on the mass of the scattering particle m and is also present at $m \longrightarrow \infty$. Therefore, in plasma, the total scattering of the longitudinal wave from ions actually is a transition scattering, whose intensity is of the same order of magnitude as the intensity of the longitudinal wave scattering from electrons. On the whole, without taking into account the transition scattering, an analysis of the processes that occur in plasma is impossible.

Another effect related to transition scattering is transition bremsstrahlung [50, 42]. Conventional bremsstrahlung occurs as follows: when particles collide, they are accelerated (or decelerated) and, as a result, emit electromagnetic waves. Since light particles (electrons) are accelerated more strongly than heavy particles (say, at the same velocity), the bremsstrahlung of electrons is much more intense (under comparable conditions) than the bremsstrahlung of heavy particles (protons, etc.). However, the aforesaid is valid only when the collisions and the corresponding bremsstrahlung occur in a vacuum. In the presence of a medium, the situation is different. As was mentioned above, radiation (transition radiation) is possible without any acceleration of the particles. Therefore, if a charge q moves in a medium (plasma) past a charge q', radiation appears even without any noticeable acceleration of some of these charges. This radiation is called transition bremsstrahlung. The physical nature of transition bremsstrahlung can be most easily understood by decomposing the field $\mathbf{E}$ and polarization $\mathbf{P} = [(\varepsilon - 1)/4\pi]\mathbf{E}$ of a uniformly moving charge q into waves with a wave vector $\mathbf{k}_0$; the frequency of these waves is $\omega_0 = \mathbf{k}_0\mathbf{v}$, where $\mathbf{v}$ is the velocity of the charge. These waves give rise to permittivity waves with the same ω_0 and $\mathbf{k}_0$. The permittivity waves are scattered from the other charges q', which results in transition bremsstrahlung.

Transition radiation, as well as transition scattering and bremsstrahlung, which are closely related to it, are considered in many publications and in a special book [42].

In this lecture, the problems were only briefly reviewed. However, I hope that it has clearly demonstrated the significance of the given area of research for physics (in the case of transition radiation, the transition counters and the applications in plasma physics are of special importance).

7. CONCLUDING REMARKS

In the development of physics and (evidently) other sciences, analogies, i.e., the transfer of notions from one area to another, play an important part. Therefore, for fruitful work in science it is important to have a wide scope of scientific interests rather than to only specialize (which often happens) in some narrow field of research. This rather trivial statement was formulated in my book [20] and, as I dare to believe, has been implemented in my scientific activities. The circle of problems described in this lecture may serve as an illustration of the above statement. Namely, the V–Ch effect is an analog of the Mach supersonic radiation (cone), the excitation of mechanical vibrations in supersonic flows is analogous to the anomalous Doppler effect, and different types of transition radiation are also connected by common notions. On the whole, one can say that the analysis of different problems and effects related to radiation from uniformly moving sources forms a certain "ideology" and has its own "language." This can be seen from a number of examples, some of which are given above and others of which are given below (see also [5–7, 14, 42]; a clear popular description is given in [51]).

In 1946, Landau found that, in an isotropic plasma, even in the absence of collisions some attenuation of longitudinal (plasma) waves takes place [52]. This effect, which is called "Landau damping" (or collisionless damping), plays an important role in the physics of plasma and plasma like media (specifically, in the physics of metals and semiconductors, i.e., materials in which the conduction electrons form a kind of plasma). Landau obtained his result without any recourse to V–Ch radiation, and, undoubtedly, the mechanism of Landau damping can be understood without any references to the V–Ch effect. At the same time, the condition of Landau damping is the V–Ch condition (Eq. (8)) for the emission of a longitudinal wave by an electron (in this case, n in Eq. (8) is the refraction index for the longitudinal wave). Thus, for those who understand the mechanism of V–Ch radiation, the nature of Landau damping is evident.

Above, I have stressed that V–Ch radiation and the Doppler effect can be observed not only in the case of the motion of sources through a medium but also in the case of their motion in a narrow empty channel passing through the medium or near the medium boundary. The same is true for transition radiation and transition scattering. For example, let a charge uniformly move along a straight line over a flat surface of a medium consisting of two different materials. Then, when the charge passes over the boundary between these two media, transition radiation arises. On the whole, it always appears when some inhomogeneities occur near the trajectory of the charge, for example, when the charge enters or exits a metal waveguide (the inhomogeneity is represented by the edge of the waveguide), when the charge moves over a diffraction grating [53, 54], etc. This type of transition radiation is sometimes called diffraction radiation. The physical nature of this radiation can be most easily understood by using the aforementioned notion of the "image" charges, which move in the medium surrounding the charge trajectory (the "mirror"). The "images" move nonuniformly and emit radiation (another illustrative explanation of the effect is also possible; see, e.g., [51]).

As early as 60 years ago, at the first stage of the development of quantum electrodynamics, it became clear that, with allowance for quantum effects (primarily, electron–positron pair production, e^+e^-), the vacuum in a sufficiently strong magnetic field ceases to be the "absolute emptiness" of classical physics, in which electromagnetic waves of any frequency can freely propagate (without interacting with each other). By contrast, with allowance for the possibility of virtual pair production, the vacuum in a strong field behaves as a nonlinear anisotropic medium. The field is considered to be strong if it (e.g., the magnetic field H) is comparable to some characteristic field

$$H_c = \frac{m_e^2 c^3}{e\hbar} = 4.4 \times 10^{13}\ \mathrm{Oe}. \qquad (25)$$

The characteristic electric field E_c is determined by the same Eq. (25), and its meaning is evident: within the Compton electron wavelength $\hbar/(m_e c) = 3 \times 10^{-11}$ cm, the field $2E_c$ performs work on the electron charge e that is equal to $2\hbar E_c/(m_e c) = 2m_e c^2$ and is necessary for the production of an e^+e^- pair (its mass at rest is equal to $2m_e c^2 \sim 10^{-6}$ erg $\sim 10^6$ eV). The field given by Eq. (25) is so strong that, for years, a nonlinear polarization of the vacuum seemed to be an abstract concept. However, in 1967 and 1968, magnetized neutron stars (pulsars) with typical fields of 10^{12}–10^{13} Oe were discovered. It was also found that, in semiconductors, it is possible to model to some extent the situation typical of strong fields (25) in a vacuum. Thus, strong fields have become an object available for astrophysical and physical studies. In the framework of this lecture, the aforesaid is of interest in relation to the fact that, in strong fields in vacuum, the V–Ch effect may occur, as may transition radiation and transition scattering (see [42] and the references given there). The vacuum also behaves as a medium in a gravitational field, which makes it possible to consider, e.g., transition scattering with a transformation from gravitational waves to electromagnetic ones [42].

In addition to the aforementioned acoustic analog of the V–Ch effect, acoustic analogs also exist for the electromagnetic transition radiation and transition scattering [55]. For me, a somewhat unexpected feature proves to be the important role that is played by the transition elastic-wave radiation in elastic systems, for example, in the case of the interaction between an inhomogeneous railway track and the wheels of a uniformly moving car [56].

Presumably, analogs of the V–Ch and Doppler effects and of transition radiation and scattering are possible for wave fields of any type and, hence, with allowance for the quantum theory, for particles of any type with a transformation (radiation) of fields (particles) of some other type. An example is the transition radiation in the form of electron–positron pair production that arises when a charge crosses some boundary, e.g., the boundary of an atomic nucleus. In brief, the radiation that accompanies a uniform motion of different kinds of sources is a universal phenomenon rather than an exotic effect. Therefore, it is natural that new experimental and theoretical studies concerned with this subject continue to appear in the literature. The papers I have seen in 1995 are as follows: the transition (diffraction) radiation accompanying the motion of relativistic electrons over a diffraction grating [54], transition radiation in elastic systems [56], the transition radiation from a neutrino with a magnetic moment [57], the development of the theory of transition radiation [58, 59], the problem of the polarization of transition bremsstrahlung in plasma [60], and a detailed consideration of the transition scattering processes in an analysis of the bremsstrahlung in plasma [61] with an important application to the solar neutrino problem [62].

Thus, the area of physical research that appeared at the Lebedev Physical Institute of the Russian Academy of Sciences more than 50 years ago [1–4] and that was described in this lecture has now become an integral part of modern physics.

REFERENCES

1. P. A. Cherenkov, Dokl. Akad. Nauk SSSR **2**, 451 (1934).
2. S. I. Vavilov, Dokl. Akad. Nauk SSSR **2**, 457 (1934).
3. I. E. Tamm and I. M. Frank, Dokl. Akad. Nauk SSSR **14**, 107 (1937).
4. V. L. Ginzburg and I. M. Frank, Zh. Éksp. Teor. Fiz. **16**, 15 (1946); J. Phys. (Moscow) **9**, 353 (1945).
5. V. L. Ginzburg, *Theoretical Physics and Astrophysics*, 3rd ed. (Nauka, Moscow, 1987; Pergamon Press, Oxford, 1979).
6. V. L. Ginzburg, Tr. Fiz. Inst. im. P. N. Lebedeva, Akad. Nauk SSSR **176**, 3 (1986).
7. V. L. Ginzburg, Prog. Opt. **32**, 267 (1993).
8. O. Heaviside, Electrician, No. 23, 83 (1988); Philos. Mag. **27**, 324 (1889).
9. A. A. Tyapkin, Usp. Fiz. Nauk **112**, 731 (1974) [Sov. Phys. Usp. **17**, 288 (1974)].
10. T. R. Kaiser, Nature **247**, 400 (1974).
11. A. Sommerfeld, Gottinger Nachr. 99 (1904); Gottinger Nachr. 363 (1904); Gottinger Nachr. 201 (1905).
12. *Recollections on I. E. Tamm* (IzdAt, Moscow, 1995) [in Russian].
13. V. L. Ginzburg, Vestn. Ross. Akad. Nauk **65**, 848 (1995).
14. I. M. Frank, *The Vavilov–Cherenkov Radiation: Theoretical Problems* (Nauka, Moscow, 1988) [in Russian].
15. N. A. Dobrotin, E. L. Feĭnberg, and M. V. Fok, Priroda (Moscow), No. 11, 58 (1991).
16. P. A. Cherenkov, Dokl. Akad. Nauk SSSR **14**, 99 (1937); **14**, 103 (1937); **21**, 323 (1938).
17. I. E. Tamm, Usp. Fiz. Nauk **68**, 387 (1959); in *Collection of Scientific Works* (Nauka, Moscow, 1975), Vol. 1, p. 121 [in Russian].
18. B. M. Bolotowsky and Yu. N. Vavilov, Phys. Today **48** (12), 11 (1995).
19. P. A. Cherenkov, Phys. Rev. **52**, 378 (1937).
20. V. L. Ginzburg, *On Physics and Astrophysics* (Byuro Kvantum, Moscow, 1995) [in Russian].
21. E. L. Feĭnberg, Nauka i Zhizn’, No. 8, 34 (1990).
22. V. P. Zrelov, *The Vavilov–Cherenkov Radiation and Its Application in High-Energy Physics* (Atomizdat, Moscow, 1968), Vols. 1 and 2 [in Russian].
23. *Cherenkov Detectors and Their Application in Science and Engineering* (Nauka, Moscow, 1990) [in Russian]; CERN Courier **34** (1), 22 (1994).
24. I. E. Tamm, J. Phys. (Moscow) **1**, 439 (1939); in *Collection of Scientific Works* (Nauka, Moscow, 1973), Vol. 1, p. 77 [in Russian].
25. V. L. Ginzbrug and I. M. Frank, Dokl. Akad. Nauk SSSR **56**, 699 (1947).
26. V. L. Ginzburg, Dokl. Akad. Nauk SSSR **56**, 145 (1947).
27. V. L. Ginzburg, Dokl. Akad. Nauk SSSR **56**, 253 (1947).
28. V. L. Ginzburg, Izv. Akad. Nauk SSSR, Ser. Fiz. **11**, 165 (1947).
29. E. Fermi, Phys. Rev. **57**, 485 (1940).
30. L. D. Landau and E. M. Lifshitz, *Course of Theoretical Physics*, Vol. 8: *Electrodynamics of Continuous Media*, 3rd ed. (Nauka, Moscow, 1992; Pergamon, New York, 1984).
31. V. L. Ginzburg, Dokl. Akad. Nauk SSSR **24**, 130 (1939).
32. V. L. Ginzburg, Zh. Éksp. Teor. Fiz. **10**, 608 (1940); J. Phys. (Moscow) **3**, 101 (1940).
33. V. E. Pafomov, Tr. Fiz. Inst. im. P. N. Lebedeva, Akad. Nauk SSSR **16**, 94 (1961).
34. B. M. Bolotovskiĭ, Usp. Fiz. Nauk **62**, 201 (1957); Usp. Fiz. Nauk **75**, 295 (1961) [Sov. Phys. Usp. **4**, 781 (1962)].
35. D. A. Kirzhnits, *Some Problems in Nuclear Physics: in Memory of the 80th Anniversary of I. M. Frank* (Nauka, Moscow, 1989), p. 144 [in Russian].
36. V. L. Ginzburg, Zh. Éksp. Teor. Fiz. **10**, 589 (1940); J. Phys. (Moscow) **2**, 441 (1940).
37. I. M. Frank, Izv. Akad. Nauk SSSR, Ser. Fiz. **6**, 3 (1942).
38. V. L. Ginzburg and I. M. Frank, Dokl. Akad. Nauk SSSR **56**, 583 (1947).
39. V. L. Ginzburg and V. Ya. Éĭdman, Zh. Éksp. Teor. Fiz. **36**, 1823 (1959) [Sov. Phys. JETP **9**, 1300 (1959)].
40. B. E. Nemtsov, Zh. Éksp. Teor. Fiz. **91**, 44 (1986) [Sov. Phys. JETP **64**, 25 (1986)]; Izv. Vyssh. Uchebn. Zaved., Radiofiz. **28**, 1549 (1985); Izv. Vyssh. Uchebn. Zaved., Radiofiz. **30**, 968 (1987); B. E. Nemtsov and V. Ya. Eĭdman, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **27**, 1192 (1984); Izv. Vyssh. Uchebn. Zaved., Radiofiz. **30**, 226 (1987).
41. V. L. Ginzburg and V. P. Frolov, Pis’ma Zh. Éksp. Teor. Fiz. **43**, 265 (1986) [JETP Lett. **43**, 339 (1986)]; Phys. Lett. A **116**, 423 (1986); Tr. Fiz. Inst. im. P. N. Lebedeva, Akad. Nauk SSSR **197**, 8 (1989).
42. V. L. Ginzburg and V. N. Tsytovich, *Transition Radiation and Transition Scattering* (Nauka, Moscow, 1984; Hilger, Bristol, 1990).
43. G. M. Garibyan, Zh. Éksp. Teor. Fiz. **37**, 527 (1959) [Sov. Phys. JETP **10**, 372 (1960)]; G. M. Garibyan and Yan Shi, *X-ray Transition Radiation* (Akad. Nauk Arm. SSR, Yerevan, 1983).
44. K. A. Barsukov, Zh. Éksp. Teor. Fiz. **37**, 1106 (1959) [Sov. Phys. JETP **10**, 787 (1960)].
45. C. W. Fabjan and H. G. Fischer, Rep. Prog. Phys. **43**, 1003 (1980).
46. K. Kleinkhecht, Phys. Rep. **84**, 85 (1982).
47. V. L. Ginzburg, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **16**, 512 (1973).

48. M. L. Ter-Mikaelyan, *Influence of the Medium on Electromagnetic Processes at High Energies* (Akad. Nauk Arm. SSR, Yerevan, 1969) [in Russian]; R. A. Bagiyan and M. L. Ter-Mikaelyan, Zh. Éksp. Teor. Fiz. **81**, 1249 (1981) [Sov. Phys. JETP **54**, 666 (1981)].
49. V. L. Ginzburg and V. N. Tsytovich, Zh. Éksp. Teor. Fiz. **65**, 1818 (1973) [Sov. Phys. JETP **38**, 909 (1973)].
50. V. N. Tsytovich, Tr. Fiz. Inst. im. P. N. Lebedeva, Akad. Nauk SSSR **66**, 176 (1973).
51. B. M. Bolotovskiĭ and V. A. Davydov, *Charge, Medium, and Radiation* (Znanie, Moscow, 1989) [in Russian].
52. L. D. Landau, Zh. Éksp. Teor. Fiz. **16**, 574 (1946).
53. S. J. Smith and E. M. Purcell, Phys. Rev. **92**, 1069 (1953).
54. K. J. Woods, J. E. Walsh, R. E. Stoner, *et al.*, Phys. Rev. Lett. **74**, 3808 (1995).
55. V. I. Pavlov and A. I. Sukhorukov, Usp. Fiz. Nauk **147**, 83 (1985) [Sov. Phys. Usp. **28**, 784 (1985)].
56. A. I. Vesnitskiĭ, A. V. Kononov, and A. V. Metrikin, Prikl. Mekh. Tekh. Fiz. **36**, 170 (1995); A. I. Vesnitskiĭ and A. V. Metrikin, Usp. Fiz. Nauk **166**, 1043 (1996) [Phys. Usp. **39**, 983 (1996)].
57. M. Sakuda and Y. Kurihara, Phys. Rev. Lett. **74**, 1284 (1995).
58. V. V. Krechetov, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **38**, 639 (1995).
59. I. I. Kalikinskiĭ, Zh. Tekh. Fiz. **65** (10), 131 (1995) [Tech. Phys. **40**, 1047 (1995)].
60. V. B. Korsakov and G. D. Fleĭshman, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **38**, 887 (1995).
61. V. N. Tsytovich, Usp. Fiz. Nauk **165**, 89 (1995) [Phys. Usp. **38**, 87 (1995)].
62. V. N. Tsytovich *et al.* (for the Central Laboratory of the Research Councils, England), Technical Report RAL-TR 95-066; V. N. Tsytovich, R. Bingham, U. De Anglls, and A. Forlani, Usp. Fiz. Nauk **166**, 113 (1996) [Phys. Usp. **39**, 103 (1996)].

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