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Radiation by uniformly moving sources (Vavilov – Cherenkov effect, transition radiation, and other phenomena)†

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Contents

1. Introduction

In beginning this lecture, I wish to thank the Presidium of the Russian Academy of Sciences for awarding me the M V Lomonosov Great Gold Medal, the highest award of the Academy. Certainly it is a great honour for everybody to be distinguished in such a way, but I have probably more reasons than anyone else to be proud. The fact is that I have been with the Academy since 1940 (at P N Lebedev Physical Institute — FIAN), that is almost as long as the whole of my scientific career. Equally important for me is that I E Tamm, my teacher, was also awarded the M V Lomonosov Medal in 1968. Finally, it is a pleasure to share the honour with such an eminent physicist as A Abraham.

Now, a few words about this choice of the lecture. I have been interested in many problems during my long life as is the case with many who work in theoretical physics. I had to choose between the theory of superconductivity, cosmic ray astrophysics and radiation of uniformly moving sources. I have chosen the latter option for two reasons. To begin with, I really love this problem. The word 'love' is not commonly used in the scientific literature, but this is just a matter of the historically established style. Indeed, each of us likes one thing in science and dislikes another, exactly as he does in everyday life. Perhaps I love radiation by uniformly moving sources because my early studies were devoted to this problem, and I was young at that time. The second reason for my choice lies in the fact that radiation of uniformly moving sources appears to be traditionally a field of special interest for Russian physicists, and besides, a purely academic problem. Indeed, a most conspicuous achievement in this area, the Vavilov–Cherenkov (VC) effect, was discovered by S I Vavilov and P A Cherenkov in 1934 [1,2] and explained by I E Tamm and I M Frank in 1937 [3]. Transition radiation was first investigated by I M Frank and myself in 1945 [4]. All these authors worked at the Physical Institute, and all were members of the Academy. It is worthwhile to note, that I S Tamm, I M Frank, and P A Cherenkov won the 1958 Nobel Prize in physics for the discovery and explanation of the VC effect (S I Vavilov died in 1951, before he was sixty, and Nobel Prizes are not awarded posthumously).

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2. Vavilov – Cherenkov effect

The VC effect in the true, somewhat narrow, sense of the term is essentially emission of electromagnetic waves (light) with continuous spectrum and specific angular distribution by an electric charge (e.g. electron) moving in a medium at a constant velocity $\mathbf{v}$. Radiation with a cyclic frequency ω occurs only if the charge speed v exceeds the phase velocity of light in a given transparent medium $v_{\mathrm{p}} = c/n(\omega)$, i.e.

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

where $n(\omega)$ is the index of refraction (at a frequency ω) in the medium (c is the velocity of light in vacuum). The said specificity of radiation angular distribution is reflected in the angle θ_0 between the wave vector of emitted waves $\mathbf{k}$ and the speed $\mathbf{v}$, with

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

The results (1) – (2) can be obtained using the Huygens principle according to which each point on the path of a charge uniformly and rectilinearly moving with speed v is a source of a spherical wave emitted as the charge passes the point (Fig. 1). If the condition (1) is fulfilled, these spheres have a common envelope, a cone whose apex coincides with the instantaneous charge position, the angle θ_0 being defined by expression (2).

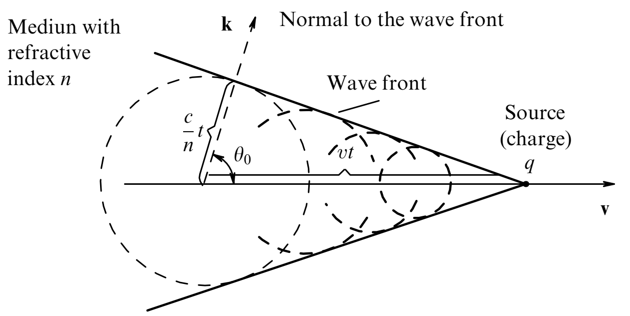

Figure 1. Generation of VC radiation ($(c/n)t$ is the light path during time t, $vt = [c/(n\cos\theta_0)]t$ is the distance covered by a charge (source) for the same period).

Disregarding the dispersion (i.e. ω-dependence of n), the angle θ_0 is the same for all frequencies ω and radiation has a clear-cut front which forms a cone with the angle of opening $\pi - 2\theta_0$ and the charge (source) in its apex (Fig. 1). This cone is totally analogous to the Mach cone that characterises a shock wave generated by the motion of a supersonic source (bullet, shell, aircraft, missile) in the air or other media, the velocity of the shock wave or sound u playing the role of the phase velocity of light $v_\mathrm{p} = c/n$ in expressions (1) and (2). The hydrodynamic (acoustic) front at the Mach cone is very sharp and easy to observe (for example, as a supersonic plane flies by) because the dispersion of sound, i.e. the dependence of its velocity u on frequency, is normally very small.

Therefore, VC radiation is the electromagnetic (optical) analogue of well-known (since the last century) acoustic phenomenon. Why was it first discovered only about 60 year ago? Doubtless, it might have been observed much earlier. On the other hand, the delay is readily explicable. First, one must have a beam of relativistic or near-relativistic charged particles to observe the VC effect in a more or less pure form. However, such beams were first available only in the Thirties (suffice it to say that there had been no accelerators until that time). Second, the motion of sources (charges) in electrodynamics (in sharp contrast to both hydrodynamics and acoustics) is, in the first place and most frequently, considered in vacuum. The VC effect in vacuum is impossible since the velocity v of particles is always lower than the velocity of light $c = 3 \times 10^{10}$ cm s^{-1} (here, we do not consider tachyons, hypothetical and in all probability non-existent superlight particles). True, this statement should be made with some reservation (see for instance Chapter 9 in Ref. [5] and [6, 7]), but on the whole, the old assertion: "a uniformly moving charge does not radiate" is quite applicable.

This dogma appears to have prejudiced the prognostication of the VC effect in the past. Nevertheless, it was actually foretold by Heaviside, an English physicist, as early as in 1888 [8]. At that time, however, even the electron was unknown, and any talk about fast particles travelling in a dielectric were out of the question. For this reason, Heaviside's prediction was put to rest and surfaced again only in 1974 [9, 10]. Calculations performed by a German physicist Sommerfeld [11] made another portent of the theory of Tamm and Frank of which they became aware only after they had reported their own findings [3]. In 1904, Sommerfeld considered a uniform motion of a charge in vacuum and came to the conclusion that it radiates at a velocity exceeding that of light ($v > c$). However, the special theory of relativity that appeared only a year later (in 1905) argued that a charge cannot propagate at a speed higher than c, and Sommerfeld's idea was discarded†. Neither he nor physicists that worked for 30 years after him came to consider the motion of a charge in a medium instead of vacuum.

This was done by Tamm and Frank [3] who calculated radiation of a charge q moving with a constant velocity $\mathbf{v}$ in a medium with the refractive index $n(\omega)$. This automatically led to the expression (2) and yielded radiation intensity (power) per unit time (i.e. at the path v)

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \frac{q^2 v}{c} \int_{c/[n(\omega)v] \leqslant 1} \left(1 - \frac{c^2}{n^2(\omega)v^2}\right) \omega \, \mathrm{d}\omega \,. \qquad (3)$$

Evidently, integration here is performed over all frequencies satisfying the condition (1). Tamm and Frank forwarded a reprint of their paper [3] to Sommerfeld who sent his reply‡ of 8 May 1937 via Austria (direct postal communication with addressees in the USSR was difficult to maintain because the Nazis were already in power). Sommerfeld wrote: 'I never thought that my calculations made in 1903 could ever have any physical implication. This confirms that the mathematical aspect of a theory outlasts changing physical concepts'.

The history of the discovery of the VC effect is described at greater length in a book by Frank [14]. The theory of this effect was considered early in this lecture. As regards its experimental aspects, VC radiation was observed by P Curie and M Curie in bottles with radium salt solutions. Nowadays, blue luminescence of water which is largely due to VC radiation can be seen by excursion parties visiting a nuclear reactor in a water tank. In 1926 – 1929, Malle (France) carried out a series of special studies on radiation in fluids subjected to gamma-rays. However, nobody before Vavilov and Cherenkov understood that the observed effect was a new phenomenon rather than simple luminescence induced by gamma-rays.

Cherenkov's experiments prompted by Vavilov were first intended to study luminescence of uranyl salt solutions caused by gamma-irradiation using the original measuring technique previously developed by Vavilov and co-workers who employed the ability of the human eye to detect such luminescence after an adaptation to complete darkness [14, 15]. Cherenkov happened to observe that the fluid (sulphuric acid) was luminous even in the absence of a solute which induced him to believe that his further work on dissertation should be given up as a bad job [15]. It was S I Vavilov who understood that the

† It ensues from the theory of relativity (tachyons disregarding) that c is the maximum velocity for an individual charge (at $v \to c$, the particle mass $m_0/\sqrt{1 - v^2/c^2}$ tends to infinity) whereas a source of radiation consisting of many particles may have any speed (see Refs [5 – 7]). This is an interesting problem, but I do not touch upon it here for lack of space.

‡ This letter was reprinted in full in "Memoirs of I E Tamm" [12], p 120. It is worth noting that Sommerfeld mentions obtaining some publications of the USSR Academy of Sciences as its foreign member. He probably received *Doklady Akademii Nauk SSSR*. It is a great pity that foreign members of the Russian Academy now have no such opportunity [13].

observed effect was radiation other than luminescence. This suggestion required new measurements which at the end provided unequivocal evidence of the discovery of a previously unknown phenomenon [1, 2]. According to Vavilov [2], it was not due to the direct effect of gamma-rays, but was associated with Compton electrons released into the fluid under the action of gamma-rays. Subsequent findings of Cherenkov [16] obtained and interpreted in collaboration with Vavilov and Frank [14, 15] revealed a number of properties of this radiation which laid the framework for deeper insights into its nature by Tamm and Frank [3].

It is clear from the foregoing that the role of S I Vavilov as the co-author of this discovery can hardly be questioned, and only the term 'VC effect' is really true. I wish to emphasise this because the opposite view can be encountered in our (Russian) literature which all physicists aware of the facts regard as groundless (see Refs [14, 5, 17, 18]). S I Vavilov himself gave reason for the term 'Cherenkov effect' to be widely used both in this country and abroad because he published only a short note on this VC effect [2] and submitted a paper [19] to the Physical Review signed by Cherenkov alone†. I cannot say why he chose to do this; perhaps it was due to his unwillingness to outshine his pupil — one of the noble actions so characteristic of him. Unfortunately, Vavilov was frequently attacked as a man, a physicist, organiser of research, and the President of the USSR Academy of Sciences. I consider all this 'criticism' to be absolutely unfounded which I have had the opportunity to state elsewhere ([20], pp 391, 393, see also Ref. [21]).

The VC effect has been extensively employed in physics (to say nothing of its value for the understanding of continuous matter electrodynamics and general physical problems). First, the VC effect may be used to measure the angle θ_0 (see (2)) and particle velocity v or (proceeding from (1)) to demonstrate directly, in the absence of effect, that $v < c/n(\omega)$ (certainly, the refractive index $n(\omega)$ in the transparent medium can and must be known). Second, radiation intensity being proportional to the squared particle charge q (see (3)), it is easy to distinguish between particles with elementary charge e (electrons, protons, etc) and nuclei with charge Ze (Z is the atomic number of the element). Indeed, radiation intensity even for the nucleus of helium ($Z = 2$) is four times that of hydrogen isotopes ($Z = 1$); it is 676 times higher for the iron nucleus ($Z = 26$) than for protons of the same velocity. Naturally, 'Cherenkov counters' (as such instruments are commonly referred to) are widely used in conjunction with accelerators and in high-energy physics at large [22, 23]. Special emphasis should be placed on the use of the VC effect in cosmic ray studies (VC radiation from atmospheric showers) and in projected facilities for detecting high-energy neutrino.

Evidently, the theory of VC radiation is beyond the scope of the present lecture (see Refs [5 – 7, 14, 22, 24] for details) in which I wish to dwell only on a few problems that I found interesting for myself).

In 1940, L I Mandelstam acting as an opponent to P A Cherenkov's thesis for the degree of Doctor of Sciences, suggested that the VC effect is equally likely to occur when a charge (source) propagates not in a continuous medium but inside a narrow empty channel made in such matter. This inference is physically relevant because VC radiation is formed not only on the charge path but also near it, at as large a distance as the wavelength of emitted light $\lambda = 2\pi c/[n(\omega)\omega]$. I M Frank and myself calculated the corresponding radiation intensity [25] which naturally decreases with increasing radius r of the empty channel in which a charge propagates axially. At $\sqrt{1 - v^2/c^2} \sim 1$, radiation is almost as high as it is in the absence of the channel provided $r/\lambda \lesssim 0.01$ (in optics, this means that $r \lesssim 5 \times 10^{-7}$ cm). A qualitatively similar picture is obtained if a channel is replaced by a slit or when a charge moves near the medium (dielectric). This is essential because the loss of energy for VC radiation when a charge moves in a medium is relatively small and ionisation losses in the immediate proximity to the trajectory prevail. Therefore, ionisation losses are excluded when a charge propagates in channels, slits or near the medium while VC radiation persists. This is important, but not crucial, for charges. However, when the Doppler effect occurs in a medium, i.e. in the case of the motion of excited atoms, the phenomenon is possible to observe only if channels or gaps are available; otherwise, the atom is destroyed. The Doppler effect can be and is actually observed also in very rarefied media, e.g. in plasma.

It may be appropriate to recall here that I used the analysis of radiation associated with the charge propagation near a medium to discuss various modes of generation of microwaves [26 – 28].

It is now time to discuss methods for the calculation of VC radiation intensity. Tamm and Frank [3] obtained the expression (3) from the solution of equations of electrodynamics in a medium. They estimated radiation intensity as a flux of the Poynting vector through the cylindrical surface surrounding the charge trajectory. Another approach consists in measuring the force which slows down the moving charge (using, of course, the same equations). The work of this force in a transparent medium is equivalent to radiation energy (3). Such calculations were made by Fermi [29] and are included in a text-book by Landau and Lifshitz [30] (see Section 115). Finally, there is one more way to obtain the same intensity (power) (3) which consists in computing electromagnetic field energy produced by a charge per unit time [31].

An explicit (so-called Hamiltonian) method may be used for this purpose. For a homogeneous isotropic stationary medium, it consists in the expansion of the field vector potential $\mathbf{A}$ in the series (see, for instance, Ref. [5] for more details)

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

where $\mathbf{e}_\lambda$ is the polarisation vector ($e_\lambda = 1$) and the index of refraction $n = \sqrt{\varepsilon}$ (ε is the dielectric permittivity of the medium assumed, for simplicity, to be nonmagnetic). The transverse electromagnetic field being examined is

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

and its energy

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

where

† Curiously, the paper [19] was first submitted to *Nature* and declined. This shows that the VC effect was apprehended as something extraordinary at that time.

$$p_{\lambda i} = \frac{\mathrm{d}q_{\lambda i}}{\mathrm{d}t}, \quad \omega_\lambda^2 = \frac{c^2}{\varepsilon} k_\lambda^2 \equiv \frac{c^2}{n^2} k_\lambda^2 . \tag{6}$$

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 $\mathbf{v}$, the current density $\mathbf{j} = q\mathbf{v}\delta[\mathbf{r} - \mathbf{r}_q(t)]$, where $\mathbf{r}_q(t)$ is the radius-vector of the charge and δ is the delta-function. Following the substitution of the expansion (4), the field equation has the form

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

Therefore, field equations are reduced to Eqns (7) for the 'field oscillators' $q_{\lambda i}(t)$. By integrating these equations and substituting the solution into (5), one obtains the field energy as summarised over energies of all oscillators. For a uniformly and rectilinearly moving charge, $\mathbf{r}_q(t) = \mathbf{v}t$, Eqns (6) are readily integrable, being equations for an oscillator which fluctuates under the effect of a harmonic force proportional to $\cos(\mathbf{k}_\lambda \mathbf{v}t)$ or $\sin(\mathbf{k}_\lambda \mathbf{v}t)$, that is with frequency

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

At $\omega = \omega_\lambda$, there is resonance, and amplitudes $q_{\lambda i}$ grow with time, i.e. radiation occurs. Obviously, in a vacuum where $n = 1$, the frequency ω is always lower than ω_λ provided, of course, that $v < c$. This means precisely that a charge uniformly moving in a vacuum does not radiate while both resonance and radiation are possible in the medium. According to (8), the condition for this is the condition $(nv/c)\cos\theta = 1$, i.e. the condition for VC radiation (2). The substitution of the solution for $q_{\lambda i}(t)$ into (5) leads to the expression $\mathcal{H}_{\mathrm{tr}} = (\mathrm{d}W/\mathrm{d}t)t$, where $\mathrm{d}W/\mathrm{d}t$ is defined by the formula (3).

To summarise, calculations using the Hamiltonian method are demonstrable and very easy to perform. This lecture gives me the opportunity to note that this technical simplicity of which I once happened to be aware stimulated my interest in theoretical physics (I graduated from the Moscow State University in 1938 trained to experiment in optics and had never before thought of becoming a theorist for want of faculties for mathematics). Certainly, this remark is not the main excuse for my having included the Hamiltonian method in this lecture. The thing is that this mode of computing the radiation energy, unlike the two others mentioned above, can almost trivially be extended to the case of anisotropic medium, i.e. non-cubical crystals and plasma in a magnetic field. In this case, the field must be expanded in normal waves capable of propagating in a proper medium (in an isotropic medium, as in a vacuum, normal waves are reduced to waves $\mathbf{A}_{\lambda i}$ present in (4), due to degeneration). Therefore, the VC effect is easy to examine in an anisotropic medium, especially in one-axial crystals [32]. Under these conditions, VC radiation gives rise to two cones which are, generally speaking, non-circular and have different polarisation (direction of the electric field in the waves). The VC effect in crystals was experimentally investigated by V P Zrelov [22].

Different aspects of the theory of VC radiation have been considered in many other papers besides those cited above. They are concerned with the generalisation to magnetic media, detailed analysis of radiation in crystals, the role of boundaries, etc. (see Refs [5 – 7, 14, 22, 33, 34] and references herein). Absorption studies [29, 35] and investigations into VC radiation for various dipoles and higher multipoles (as opposed to that for charges) are especially noteworthy (see Refs [5 – 7, 14] containing references to original works). Studies on VC radiation of multipoles are far from being completed [5 – 7] probably owing to the fact that the known particles have very small magnetic moments (to say nothing about other multipoles), while the associated radiation is equally weak and of no practical value. Radiation of a magnetic charge (monopole) might be much stronger, but such monopoles have never been observed and appear to be non-existent in nature.

Detailed analysis of all these problems and experiments using VC radiation is beyond the scope of this lecture (see Refs [22, 23]), but I cannot help considering the quantum interpretation of the VC effect.

3. Quantum theory of the Vavilov-Cherenkov effect

The classical theory of VC effect, as discussed above, is sufficiently accurate in the optical part of the spectrum. For methodological reasons, it is equally important to consider the quantum theory of this effect [36] (see also Refs [5 – 7, 14]).

What is the way to explain, in quantum language, the absence of radiation of a uniformly moving charge (or other source with zero eigenfrequency) in vacuum? To this effect, one may use the laws of conservation of energy and momentum for the case of photon emission 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 the resting mass m before (subscript 0) and after (subscript 1) the emission of a photon with the energy $\hbar\omega$ and momentum $\hbar\mathbf{k} = (\hbar\omega/c)(\mathbf{k}/k)$. It is easy to see that Eqns (9) have no solution (with $\omega > 0$) at $v < c$, that is, radiation is impossible (see formula (11) with $n = 1$ below).

To examine radiation of a source in a medium, suffice it to know one thing: the amount of radiation energy and momentum, because the particle energy $E = \sqrt{m^2c^4 + c^2p^2}$ does not change in the medium. This question is not trivial (see Ref. [5] Chapter 13), but it is easy to obtain the correct answer by intuition. Indeed, a stationary immutable medium does not effect the frequency ω while the wavelength $\lambda = \lambda_0/n$, where $\lambda_0 = 2\pi c/\omega$ is the wavelength in vacuum. Further, the wave number $k = 2\pi/\lambda = \hbar\omega n/c$. Taking this into account, Eqns (9) may be replaced by

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

The solution of these equations for ω and θ_0, where θ_0 is the angle between $\mathbf{v}_0$ and $\mathbf{k}$, leads to

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

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

Under the condition

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

(or in the case of a somewhat more accurate inequality following from (11)), the expression (11) turns into the classical expression (2). It cannot be otherwise because the condition (13) is explicitly the classicality condition (it is invariably fulfilled if the quantum constant $\hbar \to 0$). The classical limit corresponds to the neglect of recoil (a change in the particle momentum $\mathbf{p}_0$) due to 'photon emission in a medium' with momentum $\hbar\mathbf{k}$. It has already been mentioned that according to (12), radiation at $\omega > 0$ is possible only if $v_0 > c/n$ (the relation $\cos\theta_0 \leqslant 1$ is always true). In the classical limit when the result (expression (2)) does not depend on $\hbar$, the quantum computation is of purely methodological value; it may prove convenient but is optional. This is really so, and the conservation laws may be formulated in the classical domain as well provided that the relationship between the emitted electromagnetic energy $\mathcal{H}_{\mathrm{tr}}$ and the radiation momentum is taken into account. The pertinent simple calculations are reported in Refs [5 – 7]. Certainly, quantum computation of radiation intensity is equally possible [36] by generalising (3).

In the optical region, the only one where applications of the VC effect are normally feasible, the ratio $\hbar\omega/mc^2 \sim 10^{-5}$ even for electrons, i.e. quantum corrections are immaterial. In 1940, L D Landau told about my work [36] stated that it was of no interest (see Ref. [20] p. 380). It follows from the above, that he was fully justified in drawing this conclusion, and his comment hit the mark as was usual with his criticism. However, an approach to one problem is sometimes useful to apply to the solution of other problems. An example has been given above to illustrate various methods for calculating VC radiation power (3). The same refers to the application of conservation laws to the analysis of radiation in a medium which turned out to be very insightful in the Doppler effect studies under these conditions.

4. Doppler effect in the medium

Sources examined above (i.e. charges) have no natural frequency. Another important case is a source without a charge or any multipole moment constant in time but having certain natural frequency. A classical example is an oscillator, and a quantum one is an atom emitting frequency ω_0 on a certain transition (this is a frequency in the reference frame in which the source is at rest).

If such a source travels in a vacuum with constant velocity $\mathbf{v}$ (in the laboratory reference frame), the frequency of emitted waves in this frame is

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

where θ is the angle between the wave vector $\mathbf{k}$ (the direction of observation) and $\mathbf{v}$; the frequency ω_0 in (14) is the oscillation frequency in the laboratory reference frame. A change in the frequency of waves emitted by a moving source is known as the Doppler effect. Certainly, this effect also occurs in acoustics and holds for all waves regardless of their nature.

Let an oscillator or an atom (molecule) move in a transparent medium with an index of refraction $n(\omega)$, which rests in the same laboratory reference frame. Do not be confused by the fact that the source travelling in condensed matter is at risk of being destroyed, for a channel or a gap can be used in such a medium (see above).

In the presence of a medium, formula (14) is replaced by [37, 14]

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

This expression can be arrived at following the general rule, that is, substituting the velocity of light in vacuum c by the phase velocity in the medium $c/n(\omega)$ (of course, there is no need to substitute c by c/n under the root $\sqrt{1-v^2/c^2}$ because this root is related to slowing down time for a moving source and has nothing in common with radiation). Certainly, the expression (15) can be obtained automatically from the solution of the field equation for a moving emitter. Non-trivial in (15) is the appearance of the modulus which is necessary to ensure the positiveness of the frequency. If the motion occurs at a velocity lower than that of light (i.e. $v < c/n$) or at a superlight velocity (but outside the cone (2)), that is, under the condition

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

one is dealing with the ordinary, normal Doppler effect. True, the so-called complex Doppler effect is equally feasible in this situation due to dispersion, i.e. the dependence of n on ω [37, 14].

In the case of motion with a speed higher than the velocity of light (when the condition (1) is fulfilled), formula (15) without modulus would lead to negative frequency values in the angular region where

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

Radiation in the region (17), i.e. inside the cone (2) frequently referred to as the Cherenkov cone (Fig. 2), is known as the anomalous Doppler effect. The whole picture is rather complicated if dispersion is accounted for (there is an individual cone for each frequency or several cones if n shows non-monotonical dependence on ω). But I prefer to confine myself to a case which does not involve dispersion, where $n(\omega) = n = \text{const}$. Then, according to (15), the frequency $\omega \to \infty$ at the Cherenkov cone, where $(v/c)\,n\cos\theta = (v/c)\,n\cos\theta_0 = 1$, and this is true of either side of the cone (at $\theta \to \theta_0$). There is nothing more to add based on (15), and the difference between the normal and anomalous Doppler effects is actually immaterial.

It turned out that the quantum approach (to be more precise, the use of the laws of conservation of energy and momentum) allows a very important feature of the anomalous Doppler effect to be revealed [38, 5 – 7, 14]. Let us assume that an emitter represents 'a system' (atom) with two

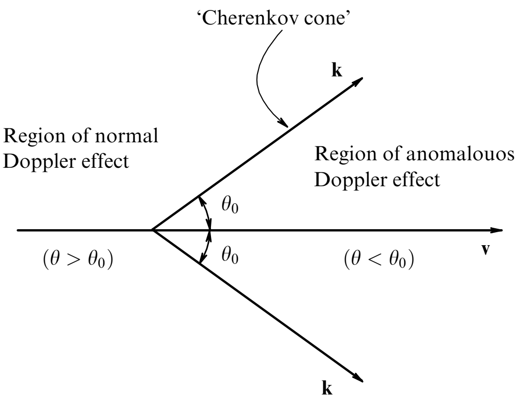

Figure 2. Regions of normal and anomalous Doppler effect.

levels, the lower one 0 and the upper one 1 (Fig. 3). Then, using the type (10) conservation laws, one needs only to change the expression for the energy of the emitter taking into consideration the internal degrees of freedom (levels). This means that the energy

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

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 same energy in the upper state 1. The energy $W_1 > W_0$, and the resting atom emits the frequency $\omega_{00} = (W_1 - W_0)/\hbar$ during transition $1 \to 0$.

The use of the conservation laws in the classical limit (13) leads to the formula (14) or (in the case of accurate computation [38]) to a somewhat more complicated expression containing terms of the order of $\hbar\omega/mc^2$. However, the quantum corrections are not so important as the following unexpected fact. Examining the signs (this is elementary algebra), it is easy to notice that in the normal Doppler effect region as well as in a vacuum, the atom passes from the upper level 1 to the lower one 0 (the direction of this transition is determined by the requirement that the emitted photon energy $\hbar\omega$ be positive, i.e from the condition that $\omega > 0$). Conversely, in the region of the anomalous Doppler effect, photon emission results in excitation of the atom leading to its transition from level 0 to level 1 (Fig. 3). This process is supported by the kinetic energy of the translational motion.

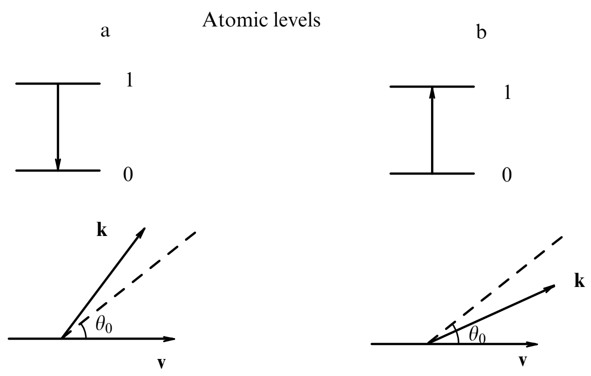

Figure 3. Transitions between levels 0 and 1 for normal and anomalous Doppler effect.

Therefore, during the motion with a velocity higher than that of light ($v > c/n$) (the only situation when the anomalous Doppler effect is possible), an emitting atom (even if not originally excited, i.e. resting at the lower level 0) undergoes excitation (shifts to level 1) and concomitantly releases a photon inside the Cherenkov cone. The initially excited atom emits outside the Cherenkov cone, i.e. at angles $\theta > \theta_0$, and passes from level 1 to level 0. It can be inferred that an atom moving faster than light undergoes continuous excitation and radiates. In the context of the classical oscillator model, this means that the oscillator is permanently excited. The anomalous Doppler effect has important implications for plasma physics. The crucial role of the VC effect in plasma and the related concepts and analogies were emphasised by I E Tamm in his Nobel lecture [17]. He also suggested that the acoustic analogue of the anomalous Doppler effect in optics is of primary importance for the analysis of vibrations arising in the flight of a supersonic aircraft (the so-called flutter).

I believe it would have been difficult to conjecture specific features of the anomalous Doppler effect unless the quantum approach had been applied [38] (to put it precisely, it follows from the above that the quantum approach itself is not as important as the use of the conservation laws). It is certainly possible to confirm this finding and go further by means of the classical or quantum computation of radiation reaction associated with the motion of an emitter in a medium. Specifically, the influence of the radiation force on oscillator vibrations can be determined for an oscillator travelling in a medium [39, 5 Chapter 7]. It turns out that the emission of waves in the region outside the Cherenkov cone (i.e. in the case of the normal Doppler effect) suppresses oscillations. On the contrary, radiation inside the Cherenkov cone corresponding to the anomalous Doppler effect swings vibrations of the oscillator and thus causes its excitation. Evidently, there is excellent agreement between this finding and the above reasoning in the quantum language.

Curiously, a few papers developing Ref [39] and some other studies in the same field were published by B E Nemtsov [40], formerly a gifted theorist and presently the noted governor of the Nizhegorodskaya province.

Hopefully the foregoing discussion will facilitate the understanding of the excitation mechanism for uniformly accelerated 'detectors' [41, 7]. This problem is extensively considered in the literature (see references in Ref. [41]) in connection with the investigations of black holes and uniformly accelerated systems (*acceleration radiation*).

5. Transition radiation at the boundary between two media

When a source having no frequency (charge, multipole) of its own is in uniform rectilinear motion in a medium, it emits radiation (VC radiation) only at velocities that exceed the velocity of light [1]. However, in drawing this assertion it is assumed that the medium is homogeneous throughout and does not change with time. If the medium is inhomogeneous or (and) variable in time, some radiation is possible at a lower velocity of a uniformly travelling source. Such radiation, first described in 1945 [4], is now called transition radiation.

The simplest case of transition radiation is exemplified by a charge that crosses the boundary between two media when moving rectilinearly and uniformly at any speed. Then, the intersection point becomes a source of transition radiation. It is easier to arrive at this conclusion when the charge comes from a vacuum and falls on a good (high-conductivity) metal that may serve as an ideal mirror (Fig. 4). It is known from electrodynamics that under these conditions the field of a charge in the vacuum is the sum of fields of a charge q moving in the vacuum in the absence of a mirror and a charge $(-q)$ which moves in a mirror to run into q (i.e. with velocity $-\mathbf{v}$); the charge $-q$ is referred to as 'the image' of charge q. As soon as the charge q crosses the boundary, it finds itself in a high-conductivity medium and is unable to produce any field in the vacuum; concurrently, the image $-q$ is lost. Therefore, from 'the point of view' of an observer, a pair of charges q and $-q$ annihilate in the vacuum. Also, it is known from electrodynamics that annihilation, as any charge acceleration (both 'charges', q and $-q$, stop abruptly at the boundary), results in radiation which is in the present case the transition radiation.

For an ideal mirror, the energy emitted to the vacuum is

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

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

In the ultrarelativistic limit (at $v \to c$),

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

$$E = \frac{mc^2}{\sqrt{1 - v^2/c^2}} \gg mc^2 . \quad (20)$$

Formulas (19) – (20) are easy to obtain [5 – 7, 42]. However, in a general case of two media with complex permittivities ε_1 and ε_2, calculations are cumbersome [4, 5, 42], and I shall not even mention their results. It is only worth noting that the above-mentioned 'backward' transition radiation (Fig. 4) is of no great practical value. True, it appears to account for the observed anticathode luminescence in X-ray tubes. In principle, it is possible to use such transition radiation to measure the particle energy E because it is included in the expression (20) for energy emitted. However, Eqn (20) contains only logarithmic E-dependence while the absolute energy value W_1 is small. However, it turned out in 1959 [43, 44] that in the case of relativistic particles, it is more reasonable to consider 'forward' transition radiation spreading in the direction of particle velocity, e.g. when it leaves matter for vacuum. In this case, very high frequencies are also emitted while the total radiation energy of a particle with charge q and mass m

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

where ω_p is the plasma frequency of matter (at high frequencies, all substances are equivalent to plasma with dielectric 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, e and m_e are the electron charge and mass, respectively).

The radiation energy W_2 is proportional to the particle energy E. Hence, the energy E can be found by measuring W_2 which is of paramount importance in physics of high-energy particles. Also, it is essential that the use of the VC effect for energy measurements is of no value when the energies are high. The point is that in the ultra-relativistic region with $v \to c$, both the Cherenkov angle θ_0 (see (2)) and the radiation intensity (3) exhibit a very low susceptibility to the particle energy $E = mc^2/\sqrt{1 - v^2/c^2}$. The 'forward' transition radiation energy W_2 is measured using the so-called transition radiation counters extensively employed in high-energy particle physics [45, 46]. To avoid misunderstanding, it should be emphasised that these counters contain a 'sandwich' of periodic series of sheets (plates) and air-gaps because the energy W_2 (see (21)) for a single boundary is very small. But the presence of many boundaries imposes limitations on the construction of a counter that in turn give rise to very interesting physics (radiation formation zones) which cannot be discussed here to save room (see Refs [5 – 7, 14, 42]).

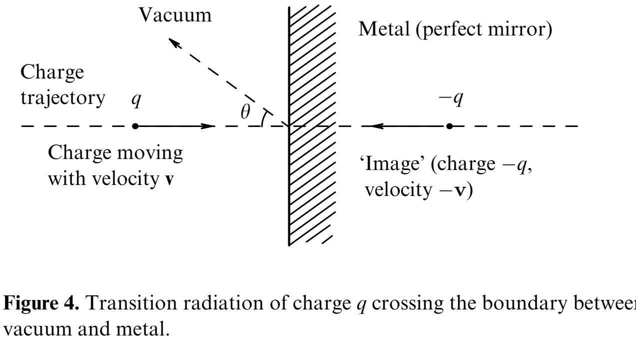

Figure 4. Transition radiation of charge q crossing the boundary between vacuum and metal.

6. Transition radiation (general case). Transition scattering. Transition bremsstrahlung

Transition radiation emitted when a source crosses a clear-cut boundary represents the simplest case. Generally speaking, transition radiation is generated whenever a source (charge) moves uniformly either in an inhomogeneous or/and non-stationary system or near it. Apart from the 'annihilation' of a source and its image described in the previous section, transition radiation may be interpreted in a different very general fashion. This can be illustrated using an isotropic transparent medium with the refractive index n. In the general case, the phase velocity of light in a medium is $v_p = c/n(\omega, \mathbf{r}, t)$, where $\mathbf{r}$ denotes the coordinates and t is the time (of course, $n(\omega, \mathbf{r}, t) = n(\omega)$ in a homogeneous and stationary medium). Light emission by a charge with velocity v is defined by the ratio $v/v_p = vn/c$. In the vacuum, $n = 1$, and there is no emission at $v = \text{const}$ (assuming that $v < c$); it is possible only in the case of charge acceleration when $v = v(t)$ and the acceleration is $w = dv/dt \neq 0$. In the case of a uniform rectilinear motion in a medium, when $v = \text{const}$, $w = 0$, the vn/c ratio can change due to the dependence of n on $\mathbf{r}$ or (and) t. This represents transition radiation, with $n(\omega, \mathbf{r}, t)$ undergoing alteration at the charge location or near it (within the zone of radiation formation).

If a source crosses the boundary between two media, index n undergoes variation at this boundary. An inhomogeneous medium (emulsion, plasma in an inhomogeneous magnetic field, etc.) offers a somewhat different variant. One more situation is interesting even though difficult to realise, with a charge uniformly propagating in a homogeneous medium and index n changing throughout it at time $t = t_0$ (or within a certain time interval near the moment t_0), e.g. due to compression. Then, a point on the trajectory occupied by the charge at time t_0 plays (even if not literally) the same role as the boundary between the two media [47, 42]. An important case of inhomogeneous medium is a periodically inhomogeneous medium, e.g. a block of plates used in transition radiation counters [48, 42]. Under such conditions, transition radiation is sometimes referred to as resonance transition radiation or transition scattering. Indeed, when a charge moves in a periodically inhomogeneous medium (sinusoidal one, see (22) below, or a medium consisting of a set of clear-cut boundaries, etc.), one may argue (from 'the point of view' of a charge) that this charge is subjected to a wave of dielectric permittivity (refractive index). Scattering of this wave at the charge gives rise to transition radiation. Nevertheless, the term 'transition scattering' were hardly relevant unless the effect persisted for a resting charge as well. In this case, there is no cause to speak about transition radiation, and the term 'transition scattering' appears adequate. In fact, the above effect is apparent for instance when a permittivity wave is incident on a stationary (fixed) charge q giving rise to an electromagnetic wave reflected (scattered) by the charge (Fig. 5).

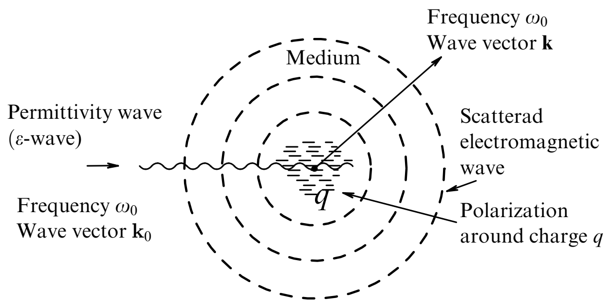

Figure 5. Schematic representation of the development of transition radiation of the permittivity wave at a stationary (fixed) charge q.

This inference is easy to understand even beyond the scope of the general transition scattering theory. For example, let us consider an isotropic transparent medium with dielectric permittivity $\varepsilon = n^2$. If an acoustic wave propagates in such a medium, the medium density is $\rho = \rho^{(0)} + \rho^{(1)} \sin(\mathbf{k}_0\mathbf{r} - \omega_0 t)$, where $\mathbf{k}_0$ and ω_0 are the wave vector and the acoustic wave frequency, respectively. However, a change in medium density ρ results in altered ε which causes the permittivity wave to propagate through the medium:

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

where $\varepsilon^{(0)}$ is the permittivity in the absence of an acoustic wave and $\varepsilon^{(1)}$ is the change in ε due to density alteration. Certainly, the permittivity wave is not necessarily induced by an acoustic wave; e.g. it may be associated with a longitudinal plasma wave.

Let us now place a fixed or infinitely heavy charge q in a medium. There is an electric field $\mathbf{E}$ and induction $\mathbf{D} = \varepsilon\mathbf{E}$ around the charge. In the absence of the wave, $\mathbf{E}$ is a Coulomb field equal to

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

In the presence of the wave (22), there is the additional polarisation in the first approximation (provided $|\varepsilon^{(1)}| \ll \varepsilon^{(0)}$):

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

Such polarisation showing no spherical symmetry (at $k_0 \neq 0$) is responsible for an electromagnetic wave with the frequency ω_0 propagating from the charge (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 one, then $k \ll k_0 = \omega_0/u$, where u is the velocity of sound (assuming, of course, that $u \ll c/\sqrt{\varepsilon^{(0)}}$).

An arising electromagnetic wave may be regarded as undergoing scattering in the same sense as with other types of scattering, e.g Thompson scattering of an electromagnetic wave at a resting electron (certainly, when speaking of the rest here, we disregard incident wave effect). If the medium is an isotropic plasma, and the incident wave is a longitudinal (plasma) one, the process of transition scattering being examined is actually the transformation of the longitudinal wave to the electromagnetic (transverse) one. This accounts for the important role of transition scattering in plasma physics which has been confirmed by different authors [5 – 7, 42] and can be illustrated by the following example. There is an electric field in a plasma longitudinal wave with a frequency close to $\omega_\mathrm{p} = \sqrt{4\pi e^2 N/m_e}$, and ε changes. Therefore, with the longitudinal wave travelling in plasma, its particles (electrons and ions) are affected by both the electric field wave and the permittivity wave. Plasma electrons undergo oscillations in the electric field and give rise to scattered electromagnetic waves (the so-called Thompson scattering) whose intensity is inversely proportional to the squared mass of the scattering particle m. Due to this, the Thompson scattering on ions is $(m_\mathrm{i}/m_e)^2$ times less intensive than that on electrons (m_e and m_i are the electron and ion masses respectively). Hence, the intensity of Thompson scattering even at the lightest ions (protons with mass $m_\mathrm{p} = 1836\, m_e$) is $(1836)^2 \approx 3.4 \times 10^6$ times lower than on electrons. On the contrary, transition scattering in the first approximation is totally independent of the scattering particle mass m and occurs even at $m \to \infty$. Therefore, virtually all longitudinal wave scattering at ions is the transition one, and its intensity appears to be of the same order as that of longitudinal waves at electrons. Generally speaking, it is impracticable to analyse plasma processes taking no account of transition scattering.

Another phenomenon related to scattering radiation is transition bremsstrahlung [50, 42]. The ordinary bremsstrahlung is known to result from particle collisions which cause their acceleration (deceleration) and are responsible for the emission of electromagnetic waves. Acceleration of light particles (electrons) is far more pronounced than that of heavy ones propagating with the same speed. Therefore, under similar conditions, bremsstrahlung of electrons is much more intensive than that of heavy particles (protons, etc). This is true, however, only of particle collisions and resulting bremsstrahlung in a vacuum. The situation is quite different in a medium. It has been shown above that radiation (transition radiation) may occur in the absence of acceleration. Therefore, if a charge q flies in a medium (plasma) closely to charge q' even without an appreciable acceleration of either of them, radiation is produced which it is natural to call transition bremsstrahlung. The physical nature of transition bremsstrahlung is readily understood if the field $\mathbf{E}$

and polarisation $\mathbf{P} = [(\varepsilon - 1)/4\pi]\,\mathbf{E}$ of a moving charge q are expanded in waves with the wave vector $\mathbf{k}_0$ and the frequency $\omega_0 = \mathbf{k}_0\mathbf{v}$, where $\mathbf{v}$ is the charge velocity. In a medium, such waves are associated with permittivity waves having the same ω_0 and $\mathbf{k}_0$ values. Such permittivity waves are scattered from other charges q' giving rise to transition bremsstrahlung.

Transition radiation and closely related transition scattering and transition bremsstrahlung have long been the objects of study and are described at greater length in a monograph [42].

This communication presents merely an overview of all these phenomena. Nevertheless, I do hope it is clear that it deals with a very important field of physics (of special interest are transition radiation counters and transition radiation applications in plasma physics).

7. Concluding remarks

Analogy, i.e the transfer of concepts from one field of science to another, is an important tool in physics and, doubtless, in other sciences. That is why a scientist must be a broad-minded person rather than a narrow specialist if he is to work fruitfully. This trivial thought is advocated in my book [20], and I dare say has guided the bulk of my scientific activities. The scope of problems dealt with in the present report appears to be a fine illustration of this view. For example, the VC effect is an analogue of the Mach supersonic radiation (cone), excitation of mechanical oscillations in supersonic flows is analogous with the anomalous Doppler effect, while various types of transition radiation are also interrelated via common notions. On the whole, it appears that the analysis of various problems and effects pertaining to the investigation of radiation produced by uniformly moving sources helps to develop a certain 'ideology' and create specific 'language'. This is easy to deduce from the examples provided earlier in this report and from those to follow (see also Refs [5 – 7, 14, 42]; a popular account of this problem can be found in a book [51]).

In 1946, L D Landau found that some attenuation of longitudinal (plasma) waves in an isotropic plasma occurs even in the absence of collisions [52]. This effect, referred to as 'Landau damping' or collisionless attenuation, is of paramount importance in physics of plasma and plasma-like media (specifically, in physics of metals and semiconductors where conduction electrons form a sort of plasma). Landau reported his discovery without any reference to VC radiation; in fact, the mechanism of Landau damping can be understood regardless of VC radiation. At the same time, Landau damping condition is precisely the VC condition (8) for the emission of a longitudinal wave by an electron (certainly, in this case n in (8) is the refractive index for the longitudinal wave). For this reason, those who understand the mechanism of VC radiation can easily perceive the nature of the Landau damping.

It has been emphasised above that the VC and the Doppler effects can be observed not only when a source travels in a medium, but also inside an empty channel in this medium or near it. The same is true of transition radiation and transition scattering. Let a charge move rectilinearly and uniformly above the flat surface of a medium composed of two different materials. Then, the charge crossing the boundary between the two phases induces transition radiation. Generally speaking, such radiation is always emitted if there are inhomogeneities near the charge path, e.g. edges of a metallic waveguide which a charge enters or escapes from; another example is a charge flying over a diffraction lattice [53, 54]. This type of transition radiation is sometimes called diffraction radiation. Its physical nature is best understood based on the previously mentioned concept of charge 'images' propagating in the medium ('mirror') around the trajectory . 'The images' emit radiation during their non-uniform motion (another demonstrable explanation of this effect is equally valid, see, for instance Ref. [51]).

As early as 60 years ago, at the inception of quantum electrodynamics, it became clear that, quantum effects (in the first place, creation of electron – positron pairs e^+e^-) being taken into consideration, the vacuum in a sufficiently strong electromagnetic field is no longer the 'absolute emptiness' of classical physics in which electromagnetic waves of any frequency propagate unopposed (without interaction with one another). On the contrary, when virtual pair creation is feasible, the vacuum in a strong field behaves like a nonlinear anisotropic system. In this case, the field (e.g. magnetic field H) is considered strong if it is comparable with a certain characteristic field

$$H_c = \frac{m_e^2 c^3}{e\hbar} = 4.4 \times 10^{13}\,\text{Oe}. \tag{25}$$

The characteristic electric field E_c is defined by the same expression (25), and its nature is quite obvious: at the Compton electron wavelength $\hbar/(m_e c) = 3 \times 10^{-11}$ cm, the field $2E_c$ does the work $2\hbar e E_c/(m_e c) = 2m_e c^2$ over the electron charge e necessary to create a e^+e^- pair with the mass at rest of $2m_e c^2 \sim 10^{-6}$ erg $\sim 10^6$ eV. The field (25) is so strong that nonlinear vacuum polarisation for a long time seemed to be pure abstraction. However, in 1967 – 1968, magnetised neutron stars (pulsars) were discovered for which $10^{12} \div 10^{13}$ Oe fields are typical. Also, it was shown that the situation characteristic of strong fields (25) in the vacuum can be simulated in semiconductors. These findings made it possible to examine strong fields in astrophysical and physical studies. For our purpose, all these facts are interesting because the VC effect, transition radiation, and transition scattering may occur in strong fields (see Ref. [42] and references herein). Vacuum also behaves as a certain medium in a gravitation field which also makes it possible to consider transition radiation associated with the transformation of gravitational waves to electromagnetic ones [42].

Apart from the aforementioned acoustic analogue of the VC effect, there are acoustic analogues of electromagnetic transition radiation and transition scattering [55]. It was somewhat surprising to learn that transition radiation of elastic waves plays an important role in elastic systems, e.g. in the case of an inhomogeneous track interacting with the wheels of a uniformly moving railway car [56].

Generally speaking, it is obvious that analogues of the VC and Doppler effects, transition radiation, and transition scattering are feasible for wave fields of any type, hence (bearing in mind the quantum theory) for particles of any type with the transformation (emission) of fields (particles) of another type. An example is transition radiation (creation) of electron – positron pairs produced by a charge crossing a boundary, e.g. the atomic nucleus boundary. In a word, radiation during the uniform motion of various sources is a universal phenomenon rather than an eccentricity. Unsurprisingly, more and more theoretical and experimental studies of this problem are being reported. To my knowledge, the papers published in 1995 are concerned with transition (diffraction) radiation of relativistic electrons travelling over diffraction lattices [54], transition radiation in elastic systems [56], transition radiation of neutrino with the magnetic moment [57], further development of the theory of transition radiation [58, 59], bremsstrahlung polarisation in plasma [61], an in-depth consideration of transition scattering in the analysis of bremsstrahlung in plasma [61] and its implications with special reference to the solar neutrino problem [62].

To summarise, there can be little doubt that the scope of physical problems first raised in the P N Lebedev Physical Institute over 50 years ago [1 – 4] and discussed in the present lecture has given rise to a self-sufficient branch of modern physics.

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