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Transition radiation: scientific implications and applications in high-energy physics

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Abstract. **In their pioneering work on transition radiation, Ginzburg and Frank showed for the first time that a charge may radiate electromagnetic waves not only because of its accelerated motion but also because of time variation of the phase velocity of electromagnetic waves in the ambient medium. This result is of very general importance for physics. For example, a charge at rest can radiate in a nonstationary medium. Transition radiation is widely used in high-energy particle detectors, mainly for identification of ultrarelativistic electrons in accelerator and collider experiments.**

My short presentation is dedicated to the remarkable discovery made by Vitaly Lazarevich Ginzburg and Il'ya Mikhailovich Frank about sixty years ago. In 1944, staff members of the Lebedev Physical Institute of the Russian Academy of Sciences (FIAN) Ginzburg and Frank submitted the paper "Radiation of a uniformly moving electron, arising when the electron passes from one medium into another" for publication to *JETP* and *J. Phys. USSR* [1], in which they predicted the existence of a new type of electromagnetic radiation, which they termed transition radiation. The title of the paper was related to the fact that transition radiation arises when a charge moving uniformly along a straight line crosses the boundary of two media with different velocities of the propagation of electromagnetic waves. Ginzburg and Frank considered the example of an electron moving from the vacuum into an ideal conductor.

Before dealing with the properties of transition radiation (TR), let me go back some ten more years — to 1934, which is remembered by physicists for paper [2] published by the FIAN postgraduate student P A Cherenkov, who worked under the guidance of S I Vavilov; the paper presented the observation of a theretofore unknown luminescence of materials due to the influence of fast electrons, presently known as Cherenkov radiation (in Russia, the term 'Vavilov – Cherenkov radiation' is often used). The nature of this radiation was explained in 1937 by Tamm and Frank [3], who showed that when a charge moves uniformly along a straight line in a homogeneous and infinite medium with a velocity exceeding the phase velocity of light propagation in this medium, radiation with properties exactly coinciding with those described in the articles by Cherenkov must arise. That such radiation should necessarily exist could have even been predicted by a student in the last years of secondary school, familiar with the fundamentals of optics. It follows, for example, from Hyugens's principle and the energy – momentum conservation laws. [1] Moreover, mechanical and acoustic (Mach shock waves) analogs of this radiation were well known.

Why did it take three whole years to understand the Cherenkov effect? This was explained well by Tamm in his Nobel lecture [4]: "I think that we have here an instructive example of a situation not uncommon in science, the progress of which is often hampered by an uncritical application of inherently sound physical principles to phenomena, lying outside of the range of validity of these principles.

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

So much so, that I. Frank and I, even after having worked out a mathematically correct theory of Vavilov – Čerenkov radiation, tried in some at present incomprehensible way to reconcile it with the maxim about the indispensibility of acceleration of charges. And only on the very next day after our first talk on our theory in the Colloquium of our Institute we perceived the simple truth: the limiting velocity for material bodies is the velocity of light in *vacuo*..."

Tamm and Frank determined the properties of Cherenkov radiation for an infinite medium. But in real experiments, the dimensions of a Cherenkov radiator are quite limited. Naturally, the desire arises to find what occurs when a charged particle crosses the boundary between the vacuum and the radiator. The answer to precisely this question is given in the aforementioned work by Ginzburg and Frank. The origin of TR, like the generation of Cherenkov radiation, can be explained 'very simply,' as was done, for instance, by Ginzburg in popular article [5]. In this connection, the question once again arises as to why this classical phenomenon, which has analogs in acoustics and mechanics, was predicted so late. In Ref. [5], Ginzburg gives the following answer: "It is difficult to doubt the fact that the obstacle to

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[1] Simple kinematical arguments allow predicting only one of the main properties of Cherenkov radiation, its narrow angular divergence. Determining the other properties, for instance, its intensity, requires solving the equations of electrodynamics.

understanding was the profound conviction that a uniformly moving charge cannot radiate. At any rate, in 1945 – 1946, when the article by I M Frank and the author had already been published, no such prejudice could have remained, but anyhow for a long time no attention was paid to transition radiation.''

For physicists, it was even more difficult to become reconciled with TR than with Cherenkov radiation. Cherenkov radiation could be considered a certain 'extreme' case, when the velocity of a charge in a medium exceeds the phase velocity of light propagation. In the case of transition radiation, no such limit exists: TR arises when a charge moves with any velocity if the electric properties of the surrounding medium (and, consequently, the phase velocity of light) changes in space and/or in time. Thus, for example, TR exists even for a charge at rest, when the refractive index of the matter surrounding the charge depends on time (the radiation process in a nonstationary medium is called transition scattering [6]).

It therefore follows from the work by Ginzburg and Frank [1] that the radiation of a charge may be related not only to its acceleration but also to the time variation of the phase velocity of electromagnetic wave propagation in the surrounding medium. Doubtless, this conclusion is of general physical significance. Regretfully, in many modern textbooks, including a textbook in physics for secondary schools, one can still encounter the obsolete assertion that a necessary condition for a charged particle to radiate is its acceleration. This is even more regretful because Cherenkov and transition radiations, related to the uniform motion of a charge along a straight line, were both discovered by our countrymen.

We now consider practical applications of TR. Although quite a few interesting proposals have been made for using TR in various fields of science and technology, actually only detectors of X-ray transition radiation (XTR) became widely applied in the identification of ultrarelativistic electrons ($\gamma = E/mc^2 \gg 1$), i.e., for the separation of electrons from heavier particles, first and foremost hadrons (pions, protons). At first sight, this problem is too special, but it actually represents one of the most important problems in experiments performed at modern accelerators and colliders. The point is that many particles playing a fundamental role in the microworld, for example, the weak interaction carriers $W^{\pm}$- and Z^0-bosons, decay emitting electrons. To identify events (often very rare) of their production involving subsequent lepton or semilepton decays under conditions of a high hadron background, detectors are required that permit identifying electrons reliably[2] (here and below, no distinction is made between electrons and positrons).

Before dealing with the methods for registering XTR, we consider its main properties, which are important for the detection of ultrarelativistic electrons. The main part of XTR from ultrarelativistic particles crossing the vacuum – matter interface is concentrated in the region of small angles to their trajectories, $\theta \lesssim 1/\gamma$, while its spectrum extends to frequencies $\omega_b \simeq \omega_p \gamma$, where ω_p is the plasma frequency of the medium. In the region $\omega > \omega_b$, the radiation intensity decreases rapidly as the frequency increases. The total TR energy radiated into the forward semisphere is given by

$$W = \frac{1}{3}\,\alpha z^2 \gamma \hbar\omega_p\,, \tag{1}$$

where $\alpha \approx 1/137$ is the fine structure constant and z is the charge of the particle in units of the electron charge. The value of $\hbar\omega_p$ for most radiators used in XTR detectors amounts to ~ 20 eV. About half of the energy emitted forward occupies the frequency range from $0.1\omega_b$ to ω_b, while the mean photon energy in this interval is $\sim \gamma\hbar\omega_p/4$. The quantities presented permit estimating the average number of photons produced at a single vacuum – matter interface: $N_{ph} \approx 0.005$. Such a low intensity is clearly insufficient for the creation of particle detectors. The method for increasing it is quite evident: it is necessary to implement a large number (hundreds and thousands) of vacuum – radiator transitions, for instance, using stacks of plates.

The production of TR in a stack of plates was considered by Garibian [7]. An important role in this process is played by the size of the zone (or length) of radiation formation, which represents a segment of the particle trajectory along which the electromagnetic wave phase changes by π. The X-ray radiation formation length L in the region of frequencies $\omega \gg \omega_p$ is

$$L = \frac{2\pi v}{\omega(1/\gamma^2 + \theta^2 + \omega_p^2/\omega^2)}\,. \tag{2}$$

Because the phases of TR wavelengths radiated in vacuum – matter and matter – vacuum transitions are opposite to each other, it follows that for plates of thickness $d \ll L$, the TR intensity is essentially reduced: it becomes proportional to $(d/L)^2$. The same holds for the distance l between the plates. In the opposite case where $d, l \gg L$, the intensities from all the boundaries add up and the total intensity becomes proportional to $2N$, where N is the number of plates in the stack. According to (1), as γ increases, the value of L increases rapidly, which imposes a practical restriction on the maximum energy of electrons registered by this detector. Besides ordered stacks of plates, porous substances like foam plastic are also used for registering XTR. The theory of XTR in porous radiators was first considered in Refs [8].

The identification of electrons is based on the dependence of XTR on the Lorentz factor γ in Eqn (1): the XTR energy intensity from electrons is nearly 300 times greater than from pions, and 2000 times greater than from protons of the same energy.

As a rule, an XTR detector consists of several modules. Each module usually comprises several hundred plates (or a block of porous material) and X-ray detectors placed behind them. The radiators are made of light materials with small Z (lithium, polyethylene) to reduce absorption of the XTR. For the same reason, the detectors have modular design. The most often used XTR counters are proportional or drift chambers or tubes with admixtures of noble gases with high Z (krypton, xenon) for enhancing the XTR registration efficiency, as well as scintillation counters with scintillators including heavy elements, for example, NaJ and CsJ crystals. The reliable identification of electrons with the aid of XTR detectors is hindered by the ionization losses of relativistic hadrons in the counters, with a distribution exhibiting a long 'tail' in the region of large losses (the Landau distribution). Methods for rejecting signals related to ionization losses of particles in the counters are considered in Ref. [9].

[2] The same may be said concerning the importance of identifying muons, but that is another task, which for obvious reasons is not considered in the present talk.

The history of the first experiments on TR registration is described in monograph [10]. Reviews [9, 11] present discussions of XTR detectors for particle identification in experiments at accelerators and colliders. The first detector applied for identifying electrons in an accelerator experiment was the one described in Ref. [12]. The radiator used in it consisted of 1350 lithium foils 55 μm thick, and proportional chambers were used for registering and measuring the XTR energy. An appropriate choice of the energy threshold for the signals from the chambers has allowed reducing the proton background by more than an order of magnitude and retaining the registration efficiency of electrons at a level of $\geqslant 90\%$.

In the experimental study of the β-decay $\Sigma^- \to ne^-\nu$ at the accelerator of the Fermi National Accelerator Laboratory (USA), it was necessary to suppress the background from the decay $\Sigma^- \to n\pi^-$, which occurs 1000 times more often. For this, an XTR detector [13] and an electromagnetic calorimeter were included in the experimental setup. The XTR detector consisted of 12 modules. Each module contained 210 layers of polypropylene (CH_2) 17 μm thick, and the distance between the layers was 1 mm. The X-ray transition radiation was registered by proportional chambers filled with the mixture 70% Xe + 30% CH_4. In this detector, made at the Konstantinov Petersburg Institute of Nuclear Physics (PINP) of the Russian Academy of Sciences (RAS), a 10^3 rejection of signals from pions was achieved, while the registration efficiency of electrons was very high ($> 99.5\%$).

We also mention the XTR detector [9] for the Helios experiment, in which the production of leptons in proton–nucleus interactions is studied at the CERN accelerator. The radiators used in the detector were made of polypropylene and drift chambers were used for XTR registration. The chambers were filled with the mixture 95% Xe + 5% C_4H_{10}. The background from particles heavier than the electron did not exceed 10^{-3}.

A peculiarity of the detector consisted in the fact that drift chambers were used not only as XTR counters but also for the reconstruction of particle tracks. This idea was further implemented in the TRT (Transition Radiation Tracker) detector of the ATLAS (*A T*oroidal *L*HC *A*pparatu*S*) facility [14]. The TRT detector consists of several hundred thousand drift tubes interspersed between propylene radiators. The ATLAS detector is intended for a broad range of research at the LHC (Large Hadron Collider) proton–proton collider under construction at CERN and designed for the energy 14 TeV in the center-of-mass system, aimed at testing the Standard Model, including searches for the Higgs particles responsible for the formation of the masses of all other particles, searches for new particles and phenomena beyond the Standard Model, investigation of the interactions of quarks and gluons, studying CP-symmetry breaking, and searching for magnetic monopoles, leptoquarks, and other exotic particles.

Thus, the research program at the ATLAS installation is to a significant extent aimed at resolving a number of fundamental problems of 21st-century physics, formulated by Ginzburg in the lecture he delivered in Stockholm on December 8, 2003, when he received the Nobel prize. It cannot be excluded that part of these problems will be resolved in the not-too-distant future (LHC is to be put into operation in 2008) owing to the application of TR detectors in the experiments.

In conclusion, we once again stress that the discovery of transition radiation was of extreme scientific significance. Detectors of transition radiation have become widespread for registering ultrarelativistic particles in experiments at accelerators and colliders. The discovery of transition radiation certainly merited a Nobel prize, but Ginzburg and Frank received Nobel prizes in physics for other research work, and Nobel prizes are known not to be given to the same person twice in one field of science.

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