

Experimental aspects of the tachyon hypothesis

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Abstract

This note is aimed at an introductory presentation of experimental characteristics of charged tachyons, deduced under the assumption that the tachyons possess standard electromagnetic interactions. In particular, Cherenkov radiation by tachyons, their ionization loss in tracking devices and the bremsstrahlung loss in electromagnetic calorimeters are considered.

1 Introduction

Currently an analysis of events containing anomalous Cherenkov rings is under progress using the data collected by the DELPHI experiment at LEP during the LEP1 and LEP2 periods. The term “anomalous rings” is related to the rings of angular radius larger than $\cos^{-1}(1/n)$ (where n is the refractive index of the Cherenkov radiator). A straightforward interpretation of such rings can be done within a framework of a hypothesis of faster-than-light particles, i.e. particles with spacelike momenta, called tachyons. This note is devoted to a description of some experimental properties of these particles which are expected when considering charged tachyons possessing standard electromagnetic interactions.

The first theoretical arguments for the possibility of the existence of particles with spacelike momenta can be found in a famous paper by Wigner in which the classification of unitary irreducible representations (UIR's) of the Poincaré group was done for the first time [1]. In the 1960's Wigner returned to discuss the UIR's of the Poincaré group corresponding to particles with spacelike momenta [2]. He has shown that quantum mechanical equations corresponding to these UIR's describe particles with imaginary rest mass moving faster than light. This almost coincided in time with the appearance of two pioneering works in which the hypothesis of faster-than-light particles was formulated explicitly, accompanied by a kinematic description of them [3] (see Sect. 2) and by their quantum field theory [4]. The particles were called *tachyons*, from the Greek word $\tau\alpha\chi\iota\sigma$ meaning *swift* [4].

These propositions immediately encountered strong objections related to the causality principle. It has been shown in several papers [5, 6, 7], in agreement with an earlier remark by Einstein [8] (see also [9, 10, 11]), that by using tachyons as information carriers one can build a causal loop, making possible information transfer to the past time of an observer. This is deduced from the apparent ability of tachyons to move backward in time, which happens when they have a negative energy provided by a suitable Lorentz transformation, this property of tachyons being a consequence of the spacelikeness of their four-momenta. A consensus was achieved that within the special relativity faster-than-light signals are incompatible with the principle of causality.

Another important problem related to tachyons was their vacuum instability. It is a well-known problem which usually appears when considering theoretical models with a Hamiltonian containing a negative mass-squared term (for an instructive description of the problem see e.g. [12]). Applied in a straightforward manner to consideration of faster-than-light particles it results in a maximum, instead of a minimum, of the Hamiltonian for tachyonic vacuum fields, and leads to the conclusion that the existence of tachyons as free particles is not possible.

Fortunately, both problems turned out to be mutually connected, and having hidden loopholes, they were resolved in the 1970's - 1980's, as described in detail in [13, 14].

In brief, the causality problem was resolved by combining the tachyon hypothesis with the modern cosmology, which establishes the preferred reference frame: so called comoving frame, in which the distribution of matter in the universe, as well the cosmic background (relic) radiation, are isotropic. This changes the situation with the causality violation by tachyons drastically, since the fast tachyons needed for a construction of a causal loop (they are called transcendent tachyons) are extremely sensitive to this frame. Therefore this frame has to be involved when considering the propagation of tachyon signals through space. These signals turn out to be ordered by the retarded causality

in the preferred frame, and after the causal ordering being established in this frame, no causal loops appear in any other frame.

Furthermore, in parallel with the causal ordering of the tachyon propagation one succeeds to get a stable tachyon vacuum which presents the minimum of the field Hamiltonian and appears, in the preferred frame, to be an ensemble of zero-energy, but finite-momentum, on-mass-shell tachyons propagating isotropically. The boundaries of this vacuum confine the acausal tachyons.

Several important properties of tachyons relevant for their experimental characteristics were deduced in [14] from the general consideration of the infinite-dimensional UIR's of the $O(2,1)$ subgroup of the Poincaré group, corresponding to faster-than-light particles. According to [14], tachyons appear as extended, axially-symmetric, stringlike objects. Their spins are directed along their momenta, to be more properly defined as helicities, always non-zero, since spinless (scalar) tachyons cannot be realizations of these UIR's. Tachyons and antitachyons, by definition, have positive and negative helicities, respectively, which may be either integer or half-odd-integer [2]. Tachyons can only be produced in pairs with antitachyons. The production of a tachyon of a high helicity state back-to-back with an antitachyon (generally speaking, with essentially non-zero opening angle) is suppressed in any reaction by the angular momentum conservation, unless the antitachyon is produced in a direction parallel to that of the tachyon, with the angular momenta of both particles compensating (or almost compensating) each other. The overall angular momentum of such a pair can be low (even zero).

Our conclusion is that no fully convincing arguments can be raised against the tachyon hypothesis. However we also conclude that in spite of a large progress made in the understanding of tachyon properties since the tachyon hypothesis first appeared, no complete and irrefutable theory describing them has so far been formulated. Therefore our predictions for tachyon behaviour in an experimental set-up will be based on the fragmentary, very often semi-intuitive and semi-quantitative approaches.

This note is organized as follows. In Section 2 several kinematic formulae for tachyons are presented. Section 3 deals with the Cherenkov radiation of charged tachyons. Characteristic dependence of the tachyon ionization loss on the tachyon velocity is sketched in Section 4. The behaviour of the charged tachyons in electromagnetic calorimeters is described in Section 5, and a comment on such a behaviour in transition radiation detectors is given in Section 6. Section 7 contains a summary of the note.

In formulae which follow below the velocity of light c and the Planck constant \hbar are taken to be equal to 1.

2 Tachyon kinematics

Faster-than-light particles were postulated in [3] possessing the following properties. They cannot traverse the light barrier and be brought to rest in any reference frame. Therefore their rest mass is imaginary, $m = i\mu$, mass squared is negative, $m^2 = -\mu^2$, which determines their four-momentum, $P = (E, \mathbf{p})$ to be spacelike, $P^2 < 0$. Namely, $E^2 - \mathbf{p}^2 = -\mu^2$. Defining the particle velocity by $\mathbf{v} = \mathbf{p}/E$ the formulae for its energy and momentum become:

$$E = \frac{\mu}{\sqrt{v^2 - 1}} \quad (2.1)$$

$$\mathbf{p} = \frac{\mu \mathbf{v}}{\sqrt{v^2 - 1}} \quad (2.2)$$

Thus, the energy and 3-momentum of the faster-than-light particle are always real. As v approaches 1 both the energy and momentum unlimitedly grow. Contrary, with the velocity increase they decrease, the energy approaching to zero at v approaching to infinity, and the 3-momentum tending to the finite value μ . The sign of the energy can be changed by a suitable Lorentz transformation,

$$E' = \frac{E - \mathbf{p}\mathbf{u}}{\sqrt{1 - u^2}} = \frac{E(1 - \mathbf{v}\mathbf{u})}{\sqrt{1 - u^2}}, \quad (2.3)$$

if $\mathbf{v}\mathbf{u} > 1$, where \mathbf{u} is the relative velocity of two reference frames. Simultaneously the sign of the time component of the particle world line is changed. A coherent explanation of these changes was suggested in [3], denoted as *the principle of reinterpretation*. Accordingly to this principle, a faster-than-light particle of negative energy moving backward in time should be interpreted as an antiparticle of positive energy moving forward in time and in the opposite spatial direction. This reinterpretation is analogous to that proposed by Dirac, Stückelberg, Wheeler and Feynman for positrons as negative energy electrons going backward in time [15, 16, 17].

3 Cherenkov radiation by tachyons

If tachyons possess electric charge they should radiate Cherenkov radiation since the laws of classical electrodynamics are also valid for charged faster-than-light particles, see [18]. The cone angle of the Cherenkov radiation by tachyons θ_c is related to the tachyon velocity v and to the radiator refraction index n in the same way as for ordinary particles:

$$\cos \theta_c = \frac{1}{nv}. \quad (3.1)$$

The validity of the formula (3.1) for tachyons follows from the fact that this formula has purely kinematic origin. It can be obtained from the kinematics of the reaction

$$t \rightarrow t' + \gamma, \quad (3.2)$$

where t designates a charged tachyon, by use, for example, of the equation of four-momentum conservation:

$$P = P' + K, \quad (3.3)$$

where P, P' are tachyon four-momenta before and after emission of a Cherenkov photon, respectively, and K is a four-momentum of the photon. Moving K to the left side of the equation (3.3) and squaring both sides of it we get

$$(P - K)^2 = (P')^2, \quad (3.4)$$

which reduces to

$$(PK) = E\omega - \mathbf{p}\mathbf{k} = 0, \quad (3.5)$$

where E and ω are energies of the initial tachyon and the Cherenkov photon, respectively, and \mathbf{p}, \mathbf{k} are their 3-momenta. For photons of optical and near-optical frequencies, propagating in medium, the relation between ω and k is given by [19]

$$\omega n(\omega) = k(\omega), \quad (3.6)$$

where $n(\omega)$ is the refraction index of the medium. Then (3.5) transforms to

$$E - p \cos \theta_c n(\omega) = 0, \quad (3.7)$$

from which (3.1) follows, taking into account that tachyon velocity v equals to p/E .

In spite of the similar kinematics, there is a drastic distinction of the dynamics of the tachyon Cherenkov radiation from that of ordinary charged particles. The latter operates with a spectrum of the radiation frequencies, ω , restricted by a narrow ω band in which the refraction index of the medium passed by the particle, $n(\omega)$, is greater than c/u , where u is the particle velocity. This determines the Cherenkov radiation from the ordinary particles to be restricted within optical and near ultraviolet regions. For tachyons the Cherenkov radiation condition is satisfied at any radiation frequency even in the vacuum. As a result, a straightforward extrapolation of ordinary particle Cherenkov radiation to the tachyonic case leads to an infinite Cherenkov energy loss [20, 21], and the only definite prediction which can be made for the tachyon Cherenkov radiation in this case is the characteristic angle of the radiation defined by a formula (3.1) since it has a purely kinematic origin.

Therefore first of all one has to formulate general principles in a frame of which the Cherenkov radiation of tachyons has to be considered. This consideration has to be carried out within a Lorentz-non-invariant approach to the tachyon Cherenkov radiation, which is a mandatory condition for any tachyon theory [13, 14]. This restricts the maximum frequency of the tachyon Cherenkov radiation in the lab system to the so called quantum limit, $\omega_{max} = E_t$, where E_t is the tachyon energy in this system. Further, the problem of the intrinsic size of a tachyon has to be addressed. In order to understand why this problem is very important in the tachyonic case, it is worthwhile to consider a hypothetical Cherenkov radiation from spinless (scalar) tachyons.

Scalar tachyons have to possess some kind of spherical symmetry. Let us consider first the case of a point-like tachyon. As was estimated in [22], the Cherenkov energy loss of point-like charged tachyons per unit length is extremely high converting the tachyons into virtual, rather than free, particles. This induces an idea to consider the tachyons possessing finite sizes. Therefore the question about a tachyon form-factor, i.e. the question about the tachyon size and the shape of its charge distribution, appears in any attempt of the realistic calculation of the tachyonic Cherenkov radiation. Interestingly, it has been understood a long time ago by A. Sommerfeld who considered, before special relativity appeared, the radiation from an electron moving in vacuum with a superluminal speed [23, 24]. His estimations of the energy loss by such an electron due to this radiation contain a characteristic size of the electron, a_0 :

$$\frac{dE}{dx} = -\frac{9e^2(v^2 - 1)}{4va_0^2}, \quad (3.8)$$

and are close to the results of modern calculations for the Cherenkov radiation by a finite-size, “spherically symmetric” charged tachyon, see [25, 26, 27]. In the case of a scalar tachyon its intrinsic size can be characterized by a single parameter only, say, a_0 , with the visual appearance of the tachyon longitudinal size affected by a Lorentz contraction to be $a = a_0\sqrt{v^2 - 1}$. Then the “spherical shape” of such a tachyon would be achieved at a rather strange value of its velocity, $v = \sqrt{2}$, which has no particular meaning among all possible tachyon velocities, $1 < v < \infty$. Thus we see that the hypothesis of a scalar

tachyon, considered from the point of view of its form-factor, looks rather unnatural ¹.

On the other hand, the situation becomes quite natural in the case of consideration of tachyons as being realizations of the UIR's of discrete series D_s^+ and D_s^- of the Poincaré group, as suggested in [14]. Such tachyons possess axially-symmetric form-factors characterized by two parameters, ρ and l_0 , the former being associated with the transversal tachyon size, and the latter with the longitudinal one. The preferred hierarchy of sizes seems to be $l_0 \gg \lambda \geq \rho$, where λ is the tachyon Compton length, $1/\mu$, and ρ may be vanishingly small. With such a hierarchy the Cherenkov energy loss in the classical limit is determined by the parameter l_0 only [18, 28], and can be expressed by a formula

$$\frac{dE}{dx} = -f \frac{2e^2}{l_0^2}, \quad (3.9)$$

where f is a factor depending on the model of the tachyon form-factor. Several models of the tachyon axially-symmetric form-factors, including one with non-zero parameter ρ , were considered in [28], and the factor f was found to be of order 1 varying by an order of magnitude. A much bigger uncertainty comes from the indefiniteness of the parameter l_0 , which may lie in the range of $10^{-12} - 10^{-10}$ cm [14]. However, even in the case of $l_0 \approx 10^{-10}$ cm the classical Cherenkov energy loss by a high energy charged tachyon would be very high, exceeding 2 GeV per μm .

Fortunately, the situation changes with a quantum-mechanical approach². It turns out that the Cherenkov radiation by tachyons in the high energy γ range is strongly affected by selection rules of angular momentum conservation. In the vacuum such a radiation is strongly suppressed for scalar tachyons and for tachyons of the minimal helicity, $|h| = 1/2$. For higher helicity tachyons the energy of a radiated Cherenkov γ is tightly restricted by the relation, obtained within the quasi-classical approach:

$$E_\gamma = \frac{\sqrt{(4h^2 - 1) p^2 - \mu^2} - E}{2h^2 - 1}, \quad (3.10)$$

where h is a tachyon helicity, and p and E are the tachyon 3-momentum and energy, respectively. An emission of the next Cherenkov γ is governed by the same relation. This leads to the discreteness of a single tachyon radiation spectrum and to the suppression of the tachyon Cherenkov radiation intensity by several orders of magnitude. An accurate estimation of this suppression depends on the quantum-mechanical widths of the spectrum lines which, unfortunately, are not calculated yet. This prevents making definite predictions for the tachyon radiation intensity in the high energy γ range.

On the other hand, the question about the tachyon behaviour in standard Cherenkov detectors is much more clear. At low radiation frequencies corresponding to optical and near ultraviolet regions, where these detectors are sensitive, the spectrum of the tachyon Cherenkov radiation is expected to be classical, i.e. continuous, and with quite loose

¹Moreover, as noticed in [14], this hypothesis fails on the observational ground since the existence of scalar tachyons would lead to the instability of photons.

²The situation is similar to the case of the classical radiation of an atomic electron which would lead to a high energy loss by the electron through the synchrotron radiation due to electron orbital motion. As well known from quantum mechanics, such a radiation is absent in the case of the atomic ground state, and the radiation has a discrete spectrum in the case of excited electron orbits, as a consequence of quantum-mechanical selection rules.

assumptions about the tachyon intrinsic size l_0 ³ it is predicted to have the shape of $\omega d\omega$, similarly to that of the radiation from ordinary particles [28]. Then the spectrum of *detected* Cherenkov photons will be determined by the condition of the optical transparency of the radiator, convoluted with the quantum efficiency of the detector of the radiation. For example, in the case of the DELPHI Barrel RICH the spectrum of detected photons extends from 5.6 eV to 7.5 eV [29].

The number of Cherenkov photons in this region is also expected, in the classical limit, to be very close to that from ordinary relativistic particles. However these expectations can fail quantum-mechanically, at angles essentially exceeding the minimal Cherenkov angles (defined by $\cos \theta_c^{min} = 1/n$), i.e. at wide angles corresponding to $v \gg 1$. The result could be a violation of the $\sin^2 \theta_c$ law for the Cherenkov radiation intensity even at low radiation frequencies, especially in low density (gaseous) Cherenkov radiators.

4 Ionization loss of tachyons

In the frame of our assumptions (standard electromagnetic interaction of tachyons) the Lorentz force acting on a charged tachyon induced by an atomic electron of an atom traversed by the tachyon (we neglect the atomic magnetic field) is reduced to

$$\mathbf{F} = e\mathbf{E}, \quad (4.1)$$

where e is the tachyon (presumably unit) charge and \mathbf{E} is the electric field of the electron which can be approximated by the Coulomb field since the electron velocities are much smaller than c . Thus, at this approximation, the force between the tachyon and the electron is:

$$\mathbf{F} = \frac{e^2}{r^3} \mathbf{r}. \quad (4.2)$$

The momentum transferred to the electron equals the time integral over the force acting in the direction perpendicular to that of the tachyon motion:

$$\Delta p_e = \int_{-\infty}^{+\infty} F_{\perp} dt = e^2 \int_{-\infty}^{+\infty} \frac{b dt}{[b^2 + (vt)^2]^{3/2}} = \frac{2e^2}{vb}. \quad (4.3)$$

Here v is a tachyon velocity and b is a tachyon impact parameter. The energy acquired by the electron equals $\Delta p_e^2/2m_e$. Thus the tachyon ionization loss is expected to be proportional to $1/v^2$, similarly to that of ordinary particles (which is natural since the ionization mechanisms are identical in both cases). Furthermore, it has to grow logarithmically with $v \rightarrow 1$ due to Lorentz contraction of the tachyon electric field which leads to an enhancement of the tachyon field strength at the periphery of the impact parameter space, $dE/dx \sim \ln(\gamma^2)/v^2$. More information about this growth can be found in textbooks on the classical electrodynamics. Though the ionization loss by a charged tachyon is not considered in these textbooks, their formulae derived for ultrarelativistic particles (having velocities close to c) are applicable to the tachyon case also. Thus, for a tachyon with a velocity $v \approx 1$

$$\frac{dE}{dx}(\gamma) = \frac{dE}{dx} \Big|_0 \left(\ln \frac{2m_e \gamma^2}{I} - 1 \right), \quad (4.4)$$

³Just excluding macroscopic scale for l_0 .

where $\gamma = 1/\sqrt{v^2 - 1}$ is a tachyon Lorentz factor, $\left.\frac{dE}{dx}\right|_0$ is the minimum ionization loss of a particle in a given medium (the mip), m_e is the electron mass, and I is a mean atomic excitation energy. Also, the density effect and the Fermi plateau are expected as usual.

For low energy tachyons (i.e for tachyons with $v \gg 1$) the ionization loss is expected to drop faster than $1/v^2$, as has been noted in [28].

5 Tachyon energy loss in electromagnetic calorimeters

Electromagnetic calorimeters are designed to measure the energy and position of electromagnetic showers produced by high energy electrons (positrons) and photons. These showers have certain characteristics which allow them to be distinguished from the electromagnetic calorimeter response to other charged particles, such as muons, pions, kaons and high energy protons. The latter leave in these calorimeters, in most of the cases, only a part of their energy due to ionization. The creation of electromagnetic showers by electrons and positrons (and by photons after their conversion to electron-positron pairs) is determined by their strong energy loss in the electromagnetic calorimeters due to bremsstrahlung radiation.

Tachyon behaviour in the electromagnetic calorimeters is expected to be very similar to that of high energy electrons, and not to other charged particles. In order to understand this let us consider first the formula for bremsstrahlung radiated by electrons and positrons colliding at high energy (we have taken electron-positron collisions in order to avoid the identity of interacting particles).

The production rates for the bremsstrahlung photons from colliding e^+e^- (initial state radiation) and from final e^+e^- (final state radiation) in the soft photon region can be calculated at once using an universal formula (see e.g. [30], where a similar formula has been applied to the calculation of the bremsstrahlung rate in the reaction $e^+e^- \rightarrow \mu^+\mu^-$):

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2} \frac{1}{E_\gamma} \int d^3\vec{p}_{e^+} d^3\vec{p}_{e^-} \sum_{i,j} \eta_i \eta_j \frac{(\vec{p}_{i\perp} \cdot \vec{p}_{j\perp})}{(P_i K)(P_j K)} \frac{dN_{e^+}}{d^3\vec{p}_{e^+}} \frac{dN_{e^-}}{d^3\vec{p}_{e^-}} \quad (5.1)$$

where K and \vec{k} denote photon four- and three-momenta, P are the 4-momenta of e^+, e^- , and \vec{p}_e are their 3-momenta, while their transversal (w.r.t. the photon direction) momenta are denoted by $\vec{p}_{i\perp} = \vec{p}_i - (\vec{n} \cdot \vec{p}_i) \cdot \vec{n}$, where \vec{n} is the photon unit vector, $\vec{n} = \vec{k}/k$; $\eta = 1$ for the initial e^- and for the outgoing e^+ , $\eta = -1$ for the initial e^+ and for the outgoing e^- , and the sum is extended over all (initial and final) electrons and positrons; the last two factors in the integrand are the final electron and positron differential spectra.

In 3-vector form, the denominator of formula (5.1) contains terms of type of $(1 - v \cos \theta_\gamma)$, where v is the particle velocity and θ_γ is the photon emission angle. For relativistic electrons $v \approx 1$ and typical values of θ_γ are of order of $1/\Gamma$, Γ being the electron Lorentz-factor, quite big for relativistic electrons. For example, electrons at LEP1 have $\Gamma \approx 10^5$, and for them $(1 - v \cos \theta_\gamma) \approx 10^{-10}$. The extreme smallness of these denominator terms is called *collinear singularity*. It determines the high bremsstrahlung rate from high energy e^+, e^- and, in turn, their showering in the electromagnetic calorimeters.

For tachyons, due to their $v > 1$ there always exists an angle θ_γ (even not very small) for which $1 - v \cos \theta_\gamma \approx 0$, thus satisfying the collinear singularity condition, i.e. ensuring a

high bremsstrahlung rate, which is practically independent of the tachyon mass (unless the tachyon becomes non-relativistic, see remark below). Therefore one can expect that the energy loss of relativistic tachyons in electromagnetic calorimeters is very similar to that of the high energy electrons. This may not be true for non-relativistic tachyons (having $v \gg 1$) since the collinear singularity condition requires wide angles of the radiation at $v \gg 1$, which is expected to be suppressed by the quantum effect of angular momentum conservation, analogously to the similar effect in the case of the wide angle Cherenkov radiation, mentioned in Sect. 3.

6 Tachyons in transition radiation detectors

Transition radiation detectors (TRD's) are used in high energy physics experiments as particle identifiers (mainly for the separation of electrons and pions), and as tracking and trigger devices. The particle identification properties of TRD's are realized when highly relativistic charged particles with the Lorentz factors $\gamma \geq 10^3$ cross many interfaces of two media with different refractive indices. However, at high particle momenta (corresponding to pion γ 's ≈ 100) the pion/electron identification starts to deteriorate due to the relativistic rise of the specific loss of pions; thus the momentum range of the TRD's identification facility is spanned usually from 1 to 10 GeV/c, though in some cases it can be extended to higher momenta by an order of magnitude.

Charged tachyons with the tachyon Lorentz factors $\gamma = 1/\sqrt{v^2 - 1} < 10^3$ are not expected to produce a significant amount of the transition radiation in TRD's, thus their energy loss in these detectors are expected to be dominated by ionization. Comparing the response of a TRD (similar to hadronic one in the case of tachyons) with the response of an electromagnetic calorimeter (similar, for tachyons, to the electron response, see Sect. 5) for a given particle one can use this comparison as an additional tachyonic signature when looking for tachyons with the mass parameters $\mu > 100$ MeV/c² in the high energy experimental data.

7 Conclusion

Several experimental aspects of the tachyon hypothesis are considered in this note related to the expected behaviour of charged tachyons in a detecting apparatus. In particular, the Cherenkov radiation by tachyons, their ionization loss in tracking devices and that in electromagnetic calorimeters and TRD's are considered. In summary, charged tachyons, if they exist, can be expected to behave in particle detectors (excepting TRD's) like high energy electrons, differing from the latter by anomalous ring Cherenkov radiation and, at high velocities, by anomalously low ionization.

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