BRADYONS AND TACHYONS

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Abstract

A brief discussion is given of the tachyon status on the base of the recent publications. The expected features of tachyons, the possible means of their detections are outlined. The properties normal particles are surveyed with emphasis on the similarities to the tachyon's features. The causes of many unsuccessful searches for tachyons are discussed. The experiments which might be sensitive to the tachyons are proposed.

Introduction

The Cherenkov radiation of the charged particles moving with greater than light phase velocity was discussed long ago [1]. Possible existence of superluminal charged particles were also taken into account [2] and [3]. They showed that such particles emit a powerful Cherenkov radiation in any media including a vacuum. But A. Einstein stated [4] "...velocities great than that of light ... have no possibilities of existence".
Such statement did not stimulate the scientific activities on tachyons. In the earlier of 60s the theoretical and later experimental efforts were retaken to justify the searches for tachyons. Several experiments at accelerators and astrophysics were performed. Many experiments with the radioactive sources were made too. But up to 1990s no crucial achievements were reached. Such results are not surprising. In order to search tachyons we must have some realistic theory of tachyon interactions, that is, some guideline. Unfortunately up to now there is no such theoretical guideline.
Nevertheless recently the experimentalists published the data which positively indicate on the existence of charged tachyons produced in the strong interaction and emitting a powerful Cherenkov radiation [5]. These results if they are true become very exciting.
There are another measurements indicating that the mass squared of the electron and muon neutrinos are probably negative [6], [7]. There is a paper claiming that the speed of gravity is much faster than light [8]. These evidences are attracting the attention of scientists. Moreover the new theoretical model was developed making possible to avoid the very crucial item, so-called causality problem [9]. Therefore the review of the tachyon status becomes acute.
In following we discuss the classification of elementary particles, the Lorentz and the Generalized Galilean transformations, related to the causality problem. We outline several unusual properties of tachyons, which might be useful in searching for them. In summary we emphasize the necessity to check the results of experiment [5] by performing new experiments.

1. Three Classes of Particles

Based on the Special Relativity (SR), three classes of particles were proposed by Bilaniuk et al [10]. The sign of 4-D wordline element, ds^2, is associated with three classes of particles. For simplicity, let us put dy = dz = 0, then

$$ds^2 = c^2dt^2 - dx^2 \begin{cases} > 0 & \text{Class I (tardyon)} \\ = 0 & \text{Class II (luxion)} \\ < 0 & \text{Class III (tachyon)} \end{cases}$$

Class I particles, tardyons, having a rest mass m_0 can not travel faster than light. For them the relation of energy, E, and momentum, p, in any inertial frame is as follows:

$$E^2 - p^2c^2 = m_0^2c^4 > 0 \tag{1}$$

We add to (1) two relations linking E, p and velocity, u, of particle

$$E = \frac{m_0c^2}{\sqrt{1-\frac{u^2}{c^2}}} \tag{2}$$

$$p = \frac{m_0u}{\sqrt{1-\frac{u^2}{c^2}}}. \tag{3}$$

The energy, E, dependence on velocity, u, is presented in Fig.1.

One notes the following features. When u = 0, E=m_0c^2, while $u \to c, E \to \infty$. For luxions the velocity u=c independent of their energy (see Fig.1, curve II). It means, for example, that if neutrinos are luxions, they should reach the earth from Supernova SN1987A simultaneously independent of their energy spectrum. Such measurements will be interesting to do. Usually tardyons and luxions become combined and labelled as bradyons. For tachyons, since $u_s/c \geq 1$ one introduces $\mu_s = -im_s$ and get the relations analogous to 1, 2 and 4

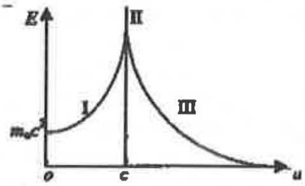

Figure 1: Energy vs. velocity for three classes of particles

$$E_s^2 - p_s^2c^2 = m_s^2c^4 < 0 \tag{4}$$

We add to 4 two relations linking E_s, p_s and velocity, u_s, fof tachyon

$$E_s = \frac{m_sc^2}{\sqrt{\frac{u_s^2}{c^2}-1}} \tag{5}$$

$$p_s = \frac{m_su_s}{\sqrt{\frac{u_s^2}{c^2}-1}}. \tag{6}$$

From the above relations the unusual extreme conditions stem out for tachyons. At $u_s \to \infty$ $E_s \to 0$, while $p_s \to m_sc$. The fact, that the tachyon has a space-like four momentum, while ordinary particle has a time-like four momentum, leads to several drastic properties. For example, in missing mass experiment tachyon production is characterized by recoil energy of accompanying tardyon beyond the usual limit corresponding to production of bradyon instead of tachyon. Next example is related to the charge exchange reaction

$$\pi^- + p \to x^0 + n.$$

If x^0 is made up of, or contains tachyons the neutron can carry higher momentum than would be otherwise allowed. These two examples are among many possible production processes that could be used to search for tachyons.

As seen from Fig.1 when tachyon looses energy its velocity increases up to infinity. If we assume that for charged tachyons the ionization loss follows the same low, as for charged bradyons, that is, $I(\beta) = I_0 \cdot \beta^{-2}$, then it becomes very difficult to detect the slowing down(means energy decreases) charged tachyons. This might be a reason of failing several experiments using in tachyon search the ionization techniques.

2. The causality problem

The essence of the causality problem consists in following. The Lorentz transformations of the coordinates (X, T) in the system S_o into x, t in the moving with velocisy,v, inertial system, S, are given by the relations

$$x = \frac{X - vT}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (7)$$

$$t = \frac{T - vXc^{-2}}{\sqrt{1 - \frac{v^2}{c^2}}}. \quad (8)$$

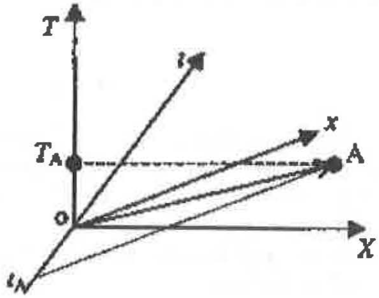

Figure 2: A 2-D diagram for Lorentz transformation

It is seen from the equation (8), that time t might be negative, if the product of the tachyon velocity in S_0 frame, U=X/T, and velocity of system S, v, becomes greater than the light velocity: $U \cdot v > c^2$. Then the event moving in positive time direction in S_0 moves in negative time direction in frame S. This is illustrated in Fig.2 by point (event) A. If in frame S_0 the event A happened earlier than event B the observer in frame S sees the time order of event vice verse, that is, the event B occurs before than event A. This is a causality paradox.
In the same condition, $U \cdot v > c^2$, the energy of tachyon becomes negative in S, while in S_0 it was positive. Combining t and E properties it was suggested so-called " reinterpretation principle" [10], meaning, that instead of tachyon moving with negative energy in negative time direction (backward) assume that antitachyon with positive energy moves in positive time direction. But this approach does not solve all problems.

3. Generalized Galileen Transformation

Recently the new approach to the solution of causality problem was proposed in papers [11], [12], [13], [14], [15]. The Generalized Galilean Transformation (GGT) was introduced which in the 2-D case looks like

$$x = \frac{X - vT}{\sqrt{1 - v^2/c^2}} \tag{9}$$

$$t = T\sqrt{1 - v^2/c^2}. \tag{10}$$

A 2-D illustration of GGT is shown in Fig.3. Clearly GGT represents a non-rectangular transformation.

The time order in GGT is always positive in any reference frame. This property can also be seen in Fig.3, since T_A and t_A both are positive for a tachyon. The problem of negative time disappears and since the synchronization is absolute under GGT, causality holds for all three types of particles.
From 9 one can get the expression for the velocity of tachyon in S for x direction

$$u = \frac{U - v}{1 - \frac{v^2}{c^2}}, \tag{11}$$

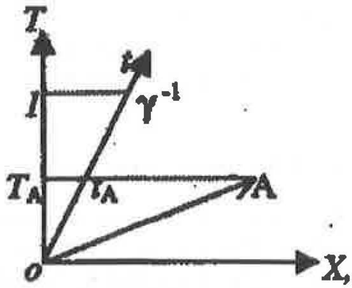

Figure 3: A 2-D diagram for GGT

where u=$\frac{dx}{dt}$ and U=$\frac{dX}{dT}$. Such transformation easily explains the Michelson experiment on the independence of the light velocity on the velocity of the inertial moving frame. This is because in Michelson experiment the light travels forth and back But GGT demands, that the light velocity must depend on the inertial system. The experimental tests of GGT predictions need to be done.

4. Where should we search for tachyons?

Any elementary particle is characterized by minimum 4 parameters:, mass, charge, spin and coupling constant. For tachyon nor theory neither experiment give any hint, where we should search tachyons. In this circumstance it is useful to look for properties of bradyons and analyze how well we know their properties. In Table 1 we make a list of bradyons and in the next column (labelled as tachyon) we ask question: are we sure that this particular particle is bradyon? First row presents a graviton. There is a paper claiming that the velocity of graviton is much higher than light [8]. Therefore the graviton might be the first candidate for tachyon. In the second row we put the weak interacting neutrinos.

The experimental data on the neutrino masses are presented below. The mass square of the electron neutrino measured in tritium decay experiment is $m^2(\nu_e) = -2.5 \pm 3.3 eV^2$ [6]. There is a statement [17]

> "There is now rather convincing evidence that neutrinos have nonzero masses. This evidence comes from the apparent observation of neutrino oscillation."

Therefore we are inclined to think, that the mass of the electron neutrino is nonzero, first, and second, the mass square of the electron neutrino more probably is negative. So put ν_e as a second candidate for tachyon.

Table 1: **Table 1. Where may we look for tachyons?**

Inter.	Bradyons	Tachyons	velocity/c	mass-sq.	Comments
Gravity	graviton	(?)	$\gg 1$ (?)	(?)	[8]
Weak	ν_e, ν_μ	(?)	$\gg 1$(?)	-(?)	[6], [7]
E-M	γ	(?)	(?)	(?)	no hint
Strong	hadrons	?	(?)	(?)	[5]
quantum optics	γ	(?)	$\gg 1$(?)	(?)	[16]

There are measurements of the muon neutrino mass square through pion decay. The result is [7]

$$m^2(\nu_\mu) = -0.01 \pm 0.023 MeV^2$$

. The mass squares of both electron and muon neutrinos seem to be negative, so error bars do not make such statement as firmly proved. In any case we may suspect that muon neutrino is a third candidate for tachyon.
The electromagnetic interaction (row 3d in Table 1) shows other superluminal evidences in quantum physics. For example, experiments in quantum optics have demonstrated that two distant events can influence each other faster than light [18], [19] and [20].

This effect might be the interference one, no tachyons. But disentangling of such not expected phenomena is necessary.
The strong interaction(row 4th in Table 1.) was a place, where many searches for tachyons were carried out (see Vodopianov's report in this Proc.). Here the first ever indication on the existence of the charged tachyon was obtained [5]. 7 events were detected having the velocities faster than light. The limits on mass($\geq$ 1 GeV) and on the production cross section($\approx 10^{-31} cm^2$) are given. These might be the first experimental restrictions on tachyon parameters.

There is one additional way to search for tachyons. Assume that tachyon does not exist as the stable particle or as the resonance with narrow width. Then we suppose that the tachyon is a pole, as the usual Regge poles and might be exchanged in the strong interactions. Depending on the properties of tachyon one can select the suitable reactions. One of the possibility is to apply this approach to the exclusive charge exchange reaction like $\pi^- + p \rightarrow \pi^0 + n$ (see A. Bogdanov's contribution to this Proceedings). This reaction is attractive for two reasons. First the differential cross section of this reaction shows a bump around the invariant four momentum transverse $t \approx -1GeV^2$. This bump is still ambiguous in interpretation. Second this reaction shows nonzero neutron polarization. In order to explain these facts one should add a new pole to the main ρ pole. There are many possibilities to do so and one of them is to apply a tachyon to this reaction as a pole. Such approach was realized and the fit of corresponding formulae to the experimental data lead to the mass and width of tachyon: 1 GeV and 0.5 GeV correspondingly. So the error bars are large the description of the experimental data is rather good.

5. The charged Tachyons

The first experiment [5] showing a positive signal for existence of the charged tachyon obliges us to look attentively at tachyon properties. One of important items is a way by which the charged tachyon looses its energy. The charged stable tachyon may emit the Cherenkov radiation in any media including a vacuum. The Lorenz - invariant formulation of the Cherenkov radiation by tachyon was given in paper [21]. Tachyon behaving as the deformed sphere looses energy per unit path length in the following way

$$\frac{dE}{ds} = \frac{9e^2}{8a_0^2}, \tag{12}$$

where e electron charge (assuming that tachyon carries a single electron charge), a_0 -radius of sphere, s is the traveling distance. The range of tachyon considered as the distance from the production point to the point of inevitable annihilation with anti-tachyon is defined by a relation

$$R = \frac{8a_0^2}{9e^2} \cdot E. \tag{13}$$

For numerical estimate it was assumed in paper [21], that tachyon has the same charge and mass as the electron has and the tachyon size is of order of the electron Compton wave length. Then we have $R = 5.5 \cdot 10^{-9}(E/m_s)$ (in centimeter). Numerically for E=m_s it follows $R = 5.5 \cdot 10^{-9} cm$. This estimate immediately leads to two important conclusions: No way to detect tachyon through its ionization losses. The only accessible way to detect tachyon is its Cherenkov radiation.

Cherenkov Radiation Spectrum. In calculating the Cherenkov radiation of the charged tachyon the following assumptions were made [22]:

1. The charged tachyon has a normal electromagnetic interaction as charged bradyons do;
2. Tachyon is an extended object;
3. Tachyon velocity might be of any value in region (1,∞).

Tachyon may emit the Cherenkov radiation of any length, since due to its velocity $u_s > c$ the spectrum of radiation does not depend on the refraction coefficient n, while the spectrum of radiation from the usual particle is limited. Therefore tachyon may emit its entire energy by radiation of photons, for example.
In general the axial-symmetric form factor was used in calculations. In this case the tachyon may have two dimensional size: transverse size, a, and the longitudinal size b. In order to explain the small production cross section in strong interaction the condition $b \gg a$ should be respected. These parameters, a and b determine the spectral distributions of the emitted photons.

For simplicity the Gaussian-like charge distribution was used which gives the following spectral distribution of the tachyon's Cherenkov radiation [22]

$$\frac{d^2E}{d\omega ds} = \frac{e^2\mu^2}{p^2} \cdot \omega \cdot \exp(\frac{-\mu^2 a_0^2 \omega^2}{4p^2}). \tag{14}$$

Here $\omega = \frac{2c}{\lambda}$ is a frequency of the emitted Cherenkov radiation, λ - wavelength, c - speed of light, p-tachyon's momentum. The maximum of the spectral distribution occurs at frequency $\omega_0 = \sqrt{2}\frac{p}{\mu a_0}$. Assuming p= $\sqrt{2}\mu$ and $a_0 = h/mc = 3.810^{-11}$ cm, one gets $\omega = 1.6 \cdot 10^{21} s^{-1}$. This corresponds to photon energy, E = 11 MeV.
So measurement of ω_0 allows to estimate the tachyon's size assuming that its velocity was defined by a Cherenkov ring diameter, its energy by an absolute measurement of the Cherenkov radiation.

Measurement of the absolute Cherenkov radiation. According to Tamm-Frank theory [23] the energy, W, of the Cherenkov light emitted by the charged bradyon per path l is

$$\frac{dW}{dl} = 2\pi^2 e^2 Z^2 \frac{\lambda_2^2 - \lambda_1^2}{\lambda_1^2 \lambda_2^2} \sin^2\theta (\frac{erg}{cm^2}. \tag{15}$$

Here e-electron charge, θ- angle of radiation, $cos\theta = 1/\beta n$. β is a velocity of a particle, n-is a refractive index of media.
For the wave length region from $\lambda_1 = 200$ nm to $\lambda_2 = 700nm$ the radiated energy is

$\frac{dW}{dl} = 1.046 n^{-9} Z^2 \sin^2\theta$, $(\frac{erg}{cm})$.

In case of 20 cm long air radiator and normal pressure for the relativistic gold ion, 100 AGeV, $\beta = 0.999956$ we expect the energy of the Cherenkov radiation $W = 6.2 \cdot 10^{-8} erg (6.2 \cdot 10^{-15} J)$. As resume one can list the following important measurements of the Cherenkov radiation which should be done: The Cherenkov radiation ring should be measured. Tachyon velocity can be extracted from such measurements. The spectral distribution of the Cherenkov radiation should be measured including its maximum. The size of tachyon can be extracted from such measurement and from point 1. The Cherenkov radiation absolute intensity should be also measured. Assuming that we can restore a whole tachyon energy by such measurements we can extract the tachyon mass from all listed above measurements.

6. The proposed experiments

We propose in following the very rough sketches of the possible experiments making emphasize on the search of the charged tachyons.

- the velocity of graviton is not yet firmly established. Therefore it is important to get the final answer on this question

- the mass square of the electron and muon neutrinos give only hint that they might be tachyons. But in order to get the unambiguous answer the additional measurements should be done. Specially the measurement of the neutrino velocity deserves a great attention. If the registrations of the explosion in SN1987 were registered synchronically by all the neutrino detectors one hopes to get the information about the velocity of neutrino. Now, when the neutrino experiment at Fermilab takes a shape it would be interesting to look for possibility of measuring the neutrino velocity in well synchronize events. Namely, the synchronizing signal from TeVatron and the neutrino signal. Might be different possibilities to make triggers for detecting neutrinos.

Some interesting suggestions on the new experiments for tachyon search were made a long ago by V. Perepelitsa [24]. He discussed two types of detectors having 4π geometrical acceptance. We put beside the bubble chambers and look at only the electronics devices, like, for example, STAR at Brookhaven National Laboratory (USA). Mainly two parameters of tachyon radiation were taken into account. Firstly the angular distributions of radiation $N(\theta) \approx \sin^{-2}\theta$, where θ is an emission angle relative to the tachyon direction. Here $cos\theta = c/v$, where v is the tachyon velocity. Secondly the tachyon energy E, which dissipates mostly through Cherenkov radiation. The most part of the radiation spectrum is concentrated around the energy $\epsilon_0(MeV) \approx 200\frac{p}{\mu}\frac{10^{-13}}{b_0}$: p is a momentum of tachyon, μ, its mass, b_0 is the largest size of tachyon(in cm). Therefore depending on the size of tachyon the radiation spectrum may last from 0.2 KeV till 2 GeV, if b_0 varies in range $10^{-13} \div 10^{-7}$ cm. The technics should be different in different energy domain. In order to define the tachyon velocity it is necessary to measure the ring of the Cherenkov radiation(its diameter). The detector should have the Electro-Magnetic Calorimeter(EMC) to be able to measure the energy E. In order to suppress the backgrounds some preliminary selection criteria should be applied. For example, in the case of pp interactions (RHIC), Time Projection Chambers should separate the even or odd charged multiplicity and select the odd charged events. It is expected in this case to suppress the backgrounds by factor of 100. The photons from π^0 production should also be eliminated. The photons from tachyon should fly on the direction of tachyon. Therefore this direction might be reconstructed by missing momentum technique. This suggestion should be numerically checked and if it is realistic might be applied.
Recently [25] it was proposed to use the extracted Au beam from RHIC. This scheme is interesting for several reasons. First of all energy of Au beam (100 AGeV) is close to the energy of Pb beam used in [5]. Second, mainly the same technique was proposed. Third, the Au beam is planned to be extracted by the bent crystal. Moreover crystal will catch only particles sitting in beam's halo. This will allow to avoid any conflict with the main heavt ion experiments at RHIC. This program foresees measurements of mother effects related to the Cherenkov radiation in the unknown region.

Summary

We may conclude that the theoretical supports for superluminal particles are growing. The first experimental data positively indicating on the possible existence of the charged tachyon produced in the strong interactions become a good stimulating factor. We emphasize the necessity to perform new experiments searching of tachyons. At accelerator tachyons might be searched by missing mass techniques, as well as through detection of predicted theoretically powerful Cherenkov radiations. Electron and muon neutrinos must be the object of careful investigations as possible candidates for tachyons. It will be the great project to measure directly at accelerators or in astrophysics the velocity of neutrinos. The direct measurements of the mass square and velocity of a particle suspected to be tachyon must give the unambiguous answer to question about a nature of particle.
The theoretical developments aiming to give the important constraints on the mass, coupling constants, statistics, etc must be done.
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