TACHYONS: FASTER THAN LIGHT PARTICLES

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Abstract

A tachyon is a hypothetical particle that always moves with a velocity greater than the velocity of light in vacuum, *c* = 3×10^8 m/s. It has several peculiar properties such as velocity greater than that of light and can be arbitrarily large even velocity v = ∞ is allowed, energy of a tachyon decreases with increasing velocity, its energy can be negative, even though it has spin zero it is a fermion. Tachyon particles are appeared theoretically in a variety of theories but there is no experimental evidence for the existence of tachyon particles yet. However, the study of its very reason of non-existence can be a useful tool to solve the mysteries of the universe.

1. Introduction

According to their velocities, particles can be classified into three categories [1–3]: (i) particles which travel at velocities smaller than the velocity of light (bradyons) are classified as *time-like* particles (ii) particles moving with the velocity of light (luxons) are classified as *light-like* particles e.g. photons and (iii) particles which travel with velocities greater than the velocity of light (tachyons) are classified as *space-like* particles. Now consider the third category of particles which travel with velocities greater than the velocity of light. If we try to ascribe a proper (rest) mass to such particles according special relativity it will be imaginary.

In 1962, Ennackal Chandy George Sudarshan (an Indian-American Physicist) and his collaborators [2] introduced the idea of faster-than-light particles, which were subsequently named tachyons by Gerald Feinberg [4] in 1967. The name comes from the Greek word $\tau\alpha\chi\omega$ (tachys) meaning "swift, quick, fast, rapid". Tachyons have several wondeful properties [5]: (a) Velocity of tachyons is always greater than the velocity of light and can be arbitrarily large, even velocity v = ∞ is allowed (b) Energy of a tachyon increases with decreasing velocity, which means that tachyons accelerate as they lose energy. (c) Energy of a free tachyon can be negative. (d) Tachyons are fermions, even though they have spin zero [4]. (e) Tachyons obey the fundamental conservation laws of energy, momentum and electric charge [6]. (f) Tachyons can interact with ordinary *i.e.* bradyonic particles. In order to obey the conservation laws, they must carry real energy and real momentum when they interact with bradyons. Special relativity (SR) is used for particles which travel at velocities smaller than the velocity of light (bradyons). But tachyons always move faster than light. Hence, extended theory of relativity is required for faster than light phenomena, particles and reference frames. Recami [7] called this new domain as extended relativity (ER). Thus, ER is the theoretical framework which describes the motion and interactions of tachyons. Such formulation does not change SR and gives similar results. A 'bradyonic observer' travels at a velocity less than *c*, while a 'tachyonic observer' travels at a velocity greater than *c*. In this article, some properties of tachyon particles are discussed. Most of the time we have made comparisons between ordinary particles (bradyons) and tachyon particles.

2. Mass, Momentum and Energy of a Tachyon Particle

A tachyon is a particle with space-like four-momenta. The possibility of particles whose four-momenta are always space-like and whose velocities are therefore always greater *c* is not in contradiction with special relativity [4]. There are two equivalent approaches to discuss the kinematics of tachyon particles:

(a) According to theory of special relativity [8], the energy of a particle moving with velocity v is given by

$$E = \frac{m c^2}{\sqrt{1 - \frac{\mathrm{v}^2}{c^2}}}, \qquad (1)$$

where *m* is the *proper mass* or *rest mass* of the particle. We can see that, in the case of v > c, the denominator becomes imaginary. Since the energy must be a real quantity this implies that the proper mass of tachyon particle must be imaginary (since a pure imaginary number divided by another pure imaginary number is a real number). The term *proper mass* [9] is appropriate for all categories of particles including luxons whose proper mass is zero and tachyons whose proper mass is imaginary. The word *rest mass* is not suitable for a tachyon because it never comes to rest.

(b) Describing tachyons with real masses: Let us consider the proper mass $m = i m_*$ (where $i^2 = -1$ and m_* is real). With this approach the energy equation (1) becomes

$$E = \frac{m_* c^2}{\sqrt{\frac{\mathrm{v}^2}{c^2} - 1}} \qquad (2)$$

Now the denominator is real and therefore the same can be said for the mass. Here, m_* is known as *meta-mass* that is the absolute value of the proper mass of a tachyon ($m = i m_*$). Both approaches are equivalent mathematically. Generally imaginary proper mass has no physical significance and Eq. (1) is valid for ordinary particles (bradyons) that is when v < c. That is why most of the physicists are using Eq. (2) as the energy equation for a tachyon particle.

From the theory of special relativity we know that the energy of a time-like particle is related to its mass and momentum through the expression [8]

$$E^2 = m^2 c^4 + c^2 p^2 \qquad (3)$$

This quadratic equation has two solutions: one is the positive root of the equation and the other is the negative root (i.e. for a given mass *m*, this equation describes the surface of a two-sheet hyperboloid). In other words, we can say that Eq. (4) represents a two-sheeted hyperboloid of revolution around the *E* axis. A three-dimensional model of such an (E,p) surface is shown in Fig. 1(a) [2]. The slope of the hyperbola at a given point gives the velocity of the particle in the corresponding reference frame,

$$\mathrm{v} = \frac{dE}{dp} \qquad (4)$$

In the theory of relativity, the state of positive energy is associated with forward particle that means a forward particle always has a positive energy [1] and a backward particle has a negative energy. Particles can be classified according to their 'direction of movement' in time: A particle which moves to the future is called as a *forward particle* and a particle moving to the past is called a *backward particle*. A particle which has an infinite velocity exists only in the very present instant is called a *momentary particle*. According to the *switching principle* [1,9,10] a backward particle (whose energy is negative) should always be physically observed as a typical forward particle (whose energy is positive). This is also known as *reinterpretation principle*. The interpretation is such that negative energy tachyons propagating backward in time are equivalent to positive energy tachyons propagating forward in time.

The energy of a light-like particle (mass m = 0) is related to its momentum through the expression

$$E^2 = c^2 p^2 \qquad (5)$$

The three-dimensional (E,p) surface becomes a cone of revolution about the *E* axis, as shown in Fig. 1(b). In this case, slope of the curve at any given point gives the velocity $\mathrm{v} = dE/dp = c$. This represents that the particle (e.g. photon) moves always with the velocity c. There is no point at which the particle would be at rest. Here, a Lorentz transformation can take a point on the upper cone only into another point on the upper cone (Fig. 1(b)). Any transformation into a point on the lower cone appears to introduce a particle traveling with negative energy i.e. traveling backward in time.

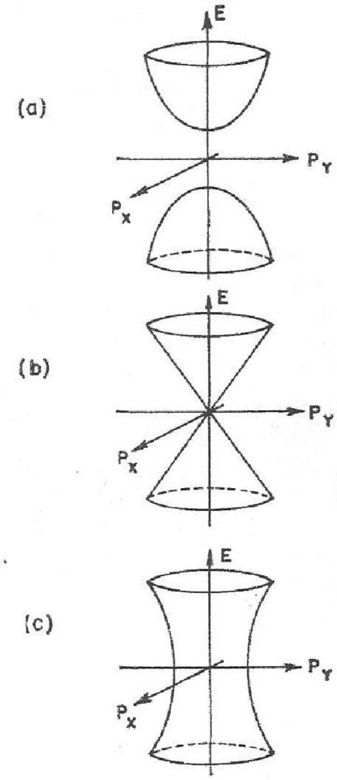

Fig. 1: Three-dimensional models of the (E,p) surfaces (a) for time-like particles, (b) for light-like particles, and (c) for space-like particles [2]. Slope of a curve at any given point gives the velocity of the particle whose energy and momentum are furnished by the coordinates of the point.

The energy of a space-like particle (tachyon) is related to its mass and momentum through the expression

$$E^2 = c^2 p^2 - m^2 c^4 \qquad (6)$$

This equation implies that the (E,p) surface is a single-sheeted hyperboloid of revolution around the *E* axis, as shown in Fig. 1(c) [2]. This represents that tachyons can change its status of a forward particle to the status of a backward one (and vice versa) [1]. Slope of the curve is everywhere greater than *c*. This represents that if particles with an imaginary proper mass do exist, their velocity would never be less than *c* and they can not be at rest.

The momentum of a tachyon particle is given by

$$p = \frac{m_* \mathrm{v}}{\sqrt{\frac{\mathrm{v}^2}{c^2} - 1}}, \qquad (7)$$

whereas the momentum of an ordinary particle (time-like particle) is given by

$$p = \frac{m \mathrm{v}}{\sqrt{1 - \frac{\mathrm{v}^2}{c^2}}} \qquad (8)$$

From Eqs. (2) and (7), it is clear that both the energy and momentum are monotonic decreasing functions of the velocity i.e. the energy of a tachyon decreases with increasing velocity. In other words, if it is required to slow down a tachyon particle, energy must be supplied to it instead of taking away from it. If the tachyon particle is to be decelerated to its lowest possible velocity, which is the velocity of light, an infinite amount of energy would have to be supplied [9].

Furthermore, the range of the energy and momentum, of a tachyon particle, are given by [4]:

$$0 < \mathrm{E} < \infty \quad , \qquad m_* \mathrm{c} < |\mathrm{p}| < \infty \qquad (9)$$

The value $\mathrm{v} = \infty$ is allowed for tachyons, and at $\mathrm{v} = \infty$ we have

$$\mathrm{E} = 0 \quad , \qquad |\mathrm{p}| = m_* c \qquad (10)$$

So tachyons at infinite velocity carry momentum but no energy. Infinite velocity tachyon having finite momentum and zero energy is known as a *transcendent tachyon* [9]. Another interesting property of tachyon: we know that the velocity of light is invariant from observer to observer. It does not depend upon its energy. But tachyons velocity varies from observer to observer and it depends upon its energy.

3. Rods and Clocks

The study of tachyons depends on the same postulates as in special relativity for bradyons [6]: (i) The laws of physics are the same in all inertial systems. (ii) The speed of light in free space has the same value *c* in all inertial systems. According to the first postulate the laws of physics that are treated as being the same in all inertial frames are mainly the conservation of energy, momentum and electric charge. Thus, we can say that tachyons conserve energy, momentum and charge in a given reference frame like bradyons. The second postulate means that electromagnetic waves travel at the same speed regardless of whether they are generated by a charged tachyon or a charged bradyon.

The tachyonic transformations have similar form to the Lorentz transformation. That is why it is expected that length contradiction and time dilation effects also apply to tachyonic rods and clocks. But it is shown that it is not exactly the same. There are some apparent differences in behavior between tachyonic and bradyonic rods and clocks which are discussed as follows:

Let us assume that there are two inertial reference frames S and S'. Frame S is bradyonic whereas frame S' is tachyonic. Let us consider a rod lying at rest along x' axis of the frame S'. The ends of the rod are at x_1' and x_2' so that its rest length is $x_2' - x_1'$. Now suppose the rod is moving with velocity v > c along the x-axis relative to an observer in frame S, so that S considers the rod to be a tachyonic object. The apparent length of the tachyonic rod as viewed in bradyonic frame S is given by

$$|x_2 - x_1| = (x_2' - x_1')\sqrt{\frac{v^2}{c^2} - 1} \qquad (11)$$

In SR, the equivalent expression for a bradyonic rod is given by

$$x_2 - x_1 = (x_2' - x_1')\sqrt{1 - \frac{v^2}{c^2}} \qquad (12)$$

In SR, that is when v < c, we observe length contraction. But for tachyons (v > c) it is shown that (a) for $c^2 < v^2 < 2c^2$ the length of the rod measured in frame S is shorter than its rest length in S', so the rod is contracted just as it is for v < c (SR). (b) For $v^2 = 2c^2$ the rod appears to have the same length in both frames. (c) For $v^2 > 2c^2$ the length of the rod appears to be dilated.

Now consider that there is a clock at rest in frame S' and the frame S' moves with a velocity v relative to frame S [1,6]. the time interval in S' is $t_2' - t_1'$. The apparent time interval as measured by S is given by

$$|t_2 - t_1| = \frac{(t_2' - t_1')}{\left|\sqrt{\frac{v^2}{c^2} - 1}\right|} \qquad (13)$$

In SR, the equivalent expression for time interval is given by

$$t_2 - t_1 = \frac{(t_2' - t_1')}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (14)$$

In SR, that is when v < c, we observe time dilation i.e. the moving clock becomes slower in measuring time than an identical clock at rest.

Here, the Eq. (13) only gives the time interval between events in frame S. It does not indicate which event appears to occur first in that particular frame. (a) For $c^2 < v^2 < 2c^2$ the clock appears to S to be slowed down just as it is for v < c (SR), (b) For $v^2 = 2c^2$ the clock appears to run at the same rate in both frames, (c) For $v^2 > 2c^2$ the clock as seen by S will appear to run fast.

Furthermore, it is also observed that a pair of tachyonic observers investigating tachyonic rods and clocks is equivalent to a pair of bradyonic observers investigating bradyonic rods and clocks [6].

4. Conclusions

A tachyon is a hypothetical particle that travels throughout its lifetime at a velocity greater than the velocity of light. That is why it is considered as a particle beyond the light barrier [9]. It has several peculiar properties such as velocity greater than that of light and can be arbitrarily large even velocity v = ∞ is allowed, energy of a tachyon decreases with increasing velocity, its energy can be negative, even though it has spin zero it is a fermion. Tachyons obey Fermi-Dirac statistics. Like other fermions, they must be created and annihilated in pairs. Ordinary particles can not cross the light-speed barrier. Similarly, tachyons can not slow down to below *c*. Because infinite amount of energy is required to cross the boundary. Tachyons lose energy as Cherenkov radiation. Special relativity (SR) is applied to the particles whose velocity is less than the velocity of light. Extended relativity (ER) can be used to describe the motion of tachyon particles [1,7]. Special relativity theory of tachyons is also known as *meta relativity* [2,9]. Such formulation does not change SR and gives similar results.

There is one fundamental question: Do tachyons exist in nature, and can they be detected? Albert Einstein [11] has said in his original paper on special relativity "…..velocities greater than that of light…have no possibility of existence." Many other physicists also think that faster than light particles can not exist. But Feinberg [4] has presented several arguments followed by reasons for the existence of faster than light particles. Experiments have also been conducted for searching them. But there is no compelling evidence for their existence [12]. Recently [13] Salem has discussed the possibility of existence of faster than light particles. According his new method simple particles (quarks and gluons) can travel faster than light. But there is no experimental proof for it. The recent experimental search for the superluminal neutrino at CERN, Switzerland, Geneva gives the negative result [14]. Hence, the existence of tachyons is one of the major challenges for both theoretical as well as experimental research. If tachyons exist we ought to find them. If they do not exist we have to find out the reason for their non-existence. So far we have found no valid reason why they could not exist. Still, much room for thought remains.

"There was a young lady named Bright

Whose speed was far faster than light

She went out one day

In a relative way

And returned home the previous night."

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